Czech Technical University in Prague

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Doctoral Thesis

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QUALITY CONTROL METHODS AND TOOLS FOR IMPROVEMENT OF EFFECTIVENESS OF MANUFACTURING PROCESSES

Doctoral Thesis

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Branch of study: Electrotechnology and Materials

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Declaration

I declare that this thesis entitled "Quality control methods and tools for improvement of effectiveness of manufacturing processes" is the result of my own research except as cited in references. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

Date ………………… Signature………………………

Acknowledgement

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Anotace

Název práce: METODY ŘÍZENÍ JAKOSTI A NÁSTROJE PRO ZEFEKTIVNĚNÍ VÝROBNÍCH PROCESŮ

Předmětem dissertační práce je odhalit využití několika moderních metod řízení a optimalizaci výrobních procesů. Cílem je dosáhnout výrobu produktů s vysokou přidanou hodnotou, monitorovat a řídit výkonnost a kvalitu samotných procesů s cílem mít méně vad, ke zvýšení produkce bez závad a zlepšit celkovou kvalitu procesů. Zavádění inovativních technologií do výrobního procesu a vytvoření matematických modelů kritérií efektivnosti realizace umožňuje hodnotít případné změny. Kombinací metod štíhlé výroby, metodologii Six Sigma a Fuzzy logiky dáva nejen širší pohled na všechny aspekty, ale také zvážuje, jak zlepšit výrobní proces a udělat jeho bez vad a s nejvetsím účinkem.

První část práce popisuje současnou situaci na trhu s elektronikou, objasňuje a vysvětluje základní pojmy z metod, jak mohou být kombinovány a používány ve výrobních procesech s cílem zvýšení a kontroly kvality.

Druhá část práce popisuje jeden z výrobních procesů, přesně výrobu desky s plošnými spoji a vývoj matematického modelu a kritéria pro hodnocení inovativních technologií a jejich zavedení do výrobního procesu.

Třetí část práce je zaměřena na metodiku pro optimalizace procesu montáži desek plošných spojů a minimalizací doby trvání dílčích procesů, které potenciálně povedou ke snížení dodací lhůty celého montážního procesu.

Čtvrtá část práce je zaměřena na optimální strategii pro zavádění inovativních technologií do výrobního procesu, a take navrhuje vytvoření manuálu systému řízení jakosti, který bude popisovat interakci mezi jednotlivými procesy v rámci organizace.

Annotation

Work title: QUALITY CONTROL METHODS AND TOOLS FOR IMPROVEMENT OF EFFECTIVENESS OF MANUFACTURING PROCESSES

The objective of this thesis is to uncover the usage of combining several modern methods for controlling and optimizing the manufacturing processes. The goal is to achieve manufacturing of high value-added products, monitor and control performance and the quality of the processes themselves in order to have fewer defects, to increase the non-defect production and improve the overall quality. Implementing innovative technologies into the manufacturing process and creating their mathematical model of effectiveness criteria of implementation allows evaluating the possible changes. Combining Lean Production, Six Sigma methodology and Fuzzy logic will give not only the broader view on all aspects, but also consider how to improve the manufacturing process and make it non defective, seamless and the most efficient.

The first part of the thesis describes the current situation of the electronics market, clarifies and explains the basic terms of methods, how they can be combined and used in manufacturing processes in order to increase and control the quality.

The second part of the thesis describes one of the manufacturing processes, i.e. Printed Circuit Board manufacturing, and development of the mathematical model and criteria for evaluation innovative technologies and their implementation into the manufacturing process.

The third part of the thesis is focused on methodology for optimizing the printed circuit board assembly process by minimizing the duration of sub processes, which potentially will decrease the lead time of the whole assembly process itself.

The fourth part of the thesis focuses on optimal strategy for implementing the innovative technologies into the manufacturing process as well as suggests the creation of policy manual of quality management system which will describe the interaction between individual processes within the organization.

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Abstract

Title: Quality control methods and tools for improvement of effectiveness of the manufacturing processes

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Abstract: The thesis is focused on different types of tools for process improvement - the synergy effect of using different tools and approaches together to drive the process to non-defective and faster execution will be examined. Implementation of innovative technologies in order to be highly competitive on the current electronics market has brought to attention. Criteria of effectiveness for implementation of innovative technologies into the manufacturing process have been analyzed. An idea of creating a system for process improvement in electronics production, which combines suitable features from Lean and Six Sigma methods, was brought to attention plus as final stage Fuzzy logic applied on top of Lean Six Sigma approach would help to replicate human reasoning and thinking in order to precisely predict and control the manufacturing process with less defects, more precision and higher quality of output products. Six Sigma is a disciplined, data-driven approach and methodology for eliminating defects (driving toward six standard deviations between the mean and the nearest specification limit) in any process - from manufacturing to transactional and from product to service. Particular phases of process improvement based on quality methods were analysed. Lean Six Sigma approach as combination of concepts would focus on reducing cycle time in processes, thus it achieves the fastest rate of improvement in cost and quality, process speed and invested capital. Fuzzy takes the role when computational control is needed, it will help to reduce the variability in a process and plan the sequence of production processes in the best manner. An idea of creating a system for process improvement in electronics production, i.e. printed circuit board manufacturing, which combines suitable features from Lean and Six Sigma methods and Fuzzy logic, was brought to attention. Optimal strategy for implementing innovations into the manufacturing process has been described as well as recommendation for designing the quality management system scheme for process interactions, which would allow to significantly increasing effectiveness of management of the organization as well as functioning of the whole quality management system.

Keywords: Six Sigma, Quality management, Lean Six Sigma, Improvement tools, Process improvement, Fuzzy Logic, Printed Circuit Board manufacturing

Introduction

Nowadays the fast development of new technologies and innovations is forcing the current manufacturing companies constantly observe the changes in the different areas of technology and science. For the successful functioning of any manufacturing company is important to constantly search and develop new technologies, which will optimize, control and increase the quality level in the current manufacturing processes.

One of the examples of the rapidly growing industry is electrical engineering and manufacturing. There are many new technologies which have been recently developed, researches for innovations and thus increase in quality level for the manufactured products. In order to organize effective manufacturing with help of technological innovations a deep analysis, based on modelling of the manufacturing processes is needed. Effectiveness of the processes is being analysed as well as how the process itself is being executed with the input values, which were not yet applied in production system. Development of the mathematical model will help to determine the results of the process in a more precise manner, before implementing it into the production, as well as the amount of needed operations, sequence of the operations, needed resources, interconnections to other processes and criteria characterizing process performance. Considering the above mentioned, process modelling allows to estimate some process before implementing it into production, which leads to time saving in terms of personnel and resources of the manufacturer itself, also establishes a smooth, non-defective production line with its best performance in regards of lead time.

The *relevance of this thesis* is connected to intense development of electrical engineering as well as simultaneous growth of its requirements in order to maintain the high standard of quality in a manufacturing process. Successful functioning and enhancement of manufacturing processes lead to products to be more competitive on the market. Quality now plays a very important role in every organization and each of the manufacturing processes. In any type of production it is impossible to have flawless products. That is why statistical quality control is very important in eliminating defects by knowing which factors have higher effect on certain topic of interest. There are many quality control tools available; these tools are very effective and widely used around the world by manufacturing companies due to their benefits. In order to improve competitiveness of the produced products is important to have not only quantitative methods, but also qualitative methods to produce a mathematical model which will classify the possible way of improvement on the early stage of innovation of the technology process. Modelling of the process allows evaluating the effectiveness of its operations and helps analyzing how it will be executed with the input parameters, which were not tested in the production system before. Modelling also allows identifying the result of the process, before implementing it into production, allows identifying the amount of needed operations, their sequence and needed resources, connection to other processes as well as factors influencing on the direction of operations.

O*bjective of the thesis* is to show which control tools can be used for process control, improvement and innovation in manufacturing of products in electrotechnology field using the combination of methodologies of Six Sigma, lean production and fuzzy logic, theory of constraints and mathematical modelling.

Object of the research is the manufacturing process of printed circuit boards. Optimization in the manufacturing process of printed circuit board assembly process is being analysed with the emphasis on individual operations.

Research methods are based on usage of elements of theory of optimization, quality management theory, theory of innovations, and theory of constraints.

Scientific contribution of the research has the following results:

1. New criteria of effectiveness for implementation of innovative technologies into a printed circuit board manufacturing process are proposed. It allows estimating the results for restructuring the current technological line for manufacturing taking into account the individual factors of effectiveness for each sub operation of the process.
2. A mathematical model for evaluation of implementing innovative technologies into the manufacturing process of printed circuit board assembly has been developed, consisting of distribution of weighting factors for each individual operation influencing on efficient functioning of manufacturing process.
3. A model for lead time minimization of printed circuit board manufacturing has been designed based on description of quality control tools to be used from six sigma and lean production methodologies with application of fuzzy theory in order

to find the optimal setup of the technological line for printed circuit board assembly process.

4. A stepwise optimization of printed circuit board assembly process, which allows minimizing the lead time of production cycle, was offered with respect to requirements for quality described in standard IPC-A-610.

Practical significance of the research ensures the efficiency of the technological innovations to be imbedded into the manufacturing processes. The results of the research based on mathematical modelling allow carefully planning and controlling the quality of the manufactured products. Models developed in the thesis allow systematizing the process of replacing of technological equipment in manufacturing line in order to be in accordance with optimal configuration to produce products with highest quality with optimum time.

Results which will be presented on the thesis defence:

1. Criteria of effectiveness for implementation of innovative technologies into a printed circuit board manufacturing process and its decomposition on individual factors taking into consideration requirements of IPC-A-610 standard.
2. A mathematical model for evaluation of implementing innovative technologies into the manufacturing process of printed circuit board consisting of distribution of weighting factors for each individual operation influencing on efficient functioning of manufacturing process.
3. A model for lead time minimization of printed circuit board manufacturing based on description of quality control tools using six sigma and lean production methodologies with application of fuzzy theory.
4. A stepwise optimization of printed circuit board assembly process, which allows minimizing the lead time of production cycle with respect to requirements for quality described in standard IPC-A-610.

Goals of the thesis

The main objective of the thesis is to describe the combined usage of several methodologies, such as six sigma, lean production and fuzzy logic in order to manufacture the products with high quality as well as to optimize manufacturing processes, design the criteria and methods of implementation of innovative technologies, which will improve the quality and competitiveness of the products by optimizing main processes. As an example of manufacturing process a printed circuit board assembly process has been taken.

For realization of the objective there are several goals to be set:

1. Design of mathematical model for evaluation of effectiveness of a company's performance based on manufacturing of printed circuit boards.
2. Review, analysis and selection of criteria of effectiveness for implementation the innovative technologies into a printed circuit board manufacturing process.
3. Design of mathematical model and criteria for lead time minimization of printed circuit board manufacturing process using six sigma and lean production methodologies with application of fuzzy theory.
4. Design of stepwise optimization process of printed circuit board manufacturing while ensuring high output product quality.
5. Analysis on performance evaluation for printed circuit board manufacturing process.

1 ANALYSIS OF THE CURRENT MODELS FOR PROCESS IMPROVEMENT

1.1 Market overview on the electrical engineering field

Electrical engineering is a field of engineering that generally deals with the study and application of electricity, electronics, and electromagnetism. Electrical engineering has now subdivided into a wide range of subfields including electronics, digital computers, power engineering, telecommunications, control systems, radio-frequency engineering, signal processing, instrumentation, and microelectronics.

At the moment electronic and electrical products manufacturing companies are under constant pressure to develop new and innovative products in shorter time cycles, at reduced cost, and with improved quality. Electrical engineering is responsible for a wide range of products, including design, developing, testing of electronic systems, electrical and electronic equipment and devices. Electronics are ubiquitous in the modern world so the industry encompasses many areas of expertise, including consumer goods, automotive, medical, and military and communications equipment. There is a strong growth in each of the individual fields of electronics. For example, in sector of computers a big part of laptops and netbooks is growing extensively as the technology is growing with the same speed and provides new functionalities against fat clients. Same applies also to the sector or mobile phones and smartphones, which is experiencing fast growing sales increase. Also from the statistics from smartphone selling, it is possible to make a conclusion about tendency for enlargement the screen resolution and size of the screen itself, which leads to expansion of functionality and improvement in the quality of image.

One of the key points in electronics is also the printed circuit board or PCB. Printed circuit boards and specialized components are made of conducting components, inductor contacts or devices, resistors, capacitors, and other components on insulation boards through conventional or non-conventional printing procedures. The miniaturization of electronic products continues to drive printed circuit board manufacturing towards smaller and more densely packed boards with increased electronic capabilities. Advancements beyond the boards include three-dimensional moulded plastic boards and the increased use of integrated circuit chips. These and other advancements will keep the manufacture of printed circuit boards a dynamic field for many years.

Market in the area of electronics and electrical engineering will stay one of the most actively progressing and perspective fields. One of the characteristics of this field is its focus on retail, which leads to the high competitive level among manufacturing companies and high quality level of manufactured products. Taken into consideration the above mentioned, the importance of the used methods is also increasing as well as means of improving product competitiveness, which all determines the relevance of the current thesis.

1.2 Current state of organization of manufacturing processes

Nowadays successful functioning of manufacturing industries is determined by applying of different methods for organization of manufacturing processes as well as finding the innovation methods. A manufacturing company shall differ with high technological level and tendency for continuous quality control and improvement for manufactured products. Main target of such companies is the profit, which shall be supported by following criteria:

- Company shall search for highly qualified workers;
- Implementation of quality management system;
- Continuous market researches;
- Innovation integration into the production.

By following such criteria the manufacturing company will be able to sustain the high level of competitiveness, be up to the latest technology trends and maintain high turnovers. Therefore, important key to success is also keeping the manufacturing process as accurate as possible, trying to predict and eliminate all possible defects, analyse possible weak points and aim to the highest possible quality to be delivered.

1.3 Methods to improve competitiveness of the manufacturing processes

Successful functioning of the manufacturing company is based on the continuous improvement of its activities, possibility to change in a fast manner to all of the market and technology changes, professional personnel and willingness of management to sustain the quality of products on the highest level. However, high level of competition on the market segment such as electronics forces to search new methods how to achieve competitive advantages through the introduction of newest quality control methods and techniques.

There is a big amount of already existing tools and methods, aimed to meet the customer requirements in regards of quality of products and thus increase the competitiveness level of the company on the global market. Majority of these methods are based on the continuous process improvement principles, i.e. Total Quality Management (TQM).

In accordance to TQM requirements, manufacturing companies shall ensure needed requirements for maintaining the high quality level of manufactured products as well as satisfying the customer needs. This fact obliges the management continuously improve and optimize production on all its stages, introduce new technologies, sustain high skill level of personnel and control the quality of manufactured products.

Nowadays provisioning the high level of quality of manufactured products as well as process efficiency increase leading to increase of competitiveness is possible with the help of development of innovative processes. Such processes are reflected in new technologies and new types of competitive products. Continuous improvement in technology makes the innovation process one of the major conditions for competitive products manufacturing, being competitive on market level and increasing the company's performance.

One of the theories in regards of innovations is to consider a technical innovation as source of the company to get the profit [1]. According to international standards innovation is defined as the final result of innovation activity, which lead to a new product or new improved technological process, which his used later on in the production process.

As for electrical engineering an approach that considers change impact or scope, common types are:

- Incremental innovations – lead to insignificant improvements for the final product or processes. They allow achieving better results through little financial and time resources;
- Transformational (or disruptive) innovations – lead to significant improvements and advantages, but they are not based on the new principal technologies or approaches;
- Radical (or breakthrough) innovations – based on fundamentally new technologies and approaches. Allow to execute new earlier inaccessible functions or the older functions with the new approach which is prevailing on the older methods;
- Integrating innovations – combine all the three classes of innovations above. Integrating innovations ensure realization of final stage of the innovative process:

realization of complex systems through optimal integration of already tested technical progress.

Current trend of the society development as well as manufacturing process development is innovative activity, which is connected to creation of new innovations, its subsequent application as an instrument to achieve high quality of the manufactured products.

Development of any area requires innovation development, specially such high tech industry as electronics. Nowadays high technical level of this industry is achieved by introduction to innovation technology and new technologies of automatic assembly of printed circuit boards such as SMT (surface mount technology) and THT (through hole technology).

Growth of the requirements for electronic equipment leads to manufacturing processes enhancement. Electronics manufacturing can be divided into several main processes, such as manufacturing of chip components, printed circuit board manufacturing, mounting of the components on PCB boards, product assembly and software installation.

From the above mentioned processes, one of the main ones which will ensure the high quality of the final product is mounting of the components on PCB boards. This process will not only ensure the high quality of final product, but also reliability, high performance and functionality of the product. That is why it is so important to ensure high quality of the product on this stage of the manufacturing process.

Tendency to satisfy high standards is one of the priority tasks of any company. In the area of electronics one of the main instruments in order to ensure the high quality of manufactured products are IPC (Association Connecting Electronics Industries) standards, which standardize the assembly and production requirements of electronic equipment and assemblies. These standards describe main steps of electronics manufacturing (see Figure 1), such as [2]:

- Design and Land Patterns (IPC 2220 – 7351);
- Acceptability of Electronic Assemblies (IPC-A-610);
- Requirements for Soldered Electronic Assemblies (J-STD-001);
- Acceptability of Electronic Assemblies (IPC-A-610);
- Requirements and Acceptance for Cable and Wire Harness Assemblies (IPC-A-620);
- Standardization and certification of equipment and etc.

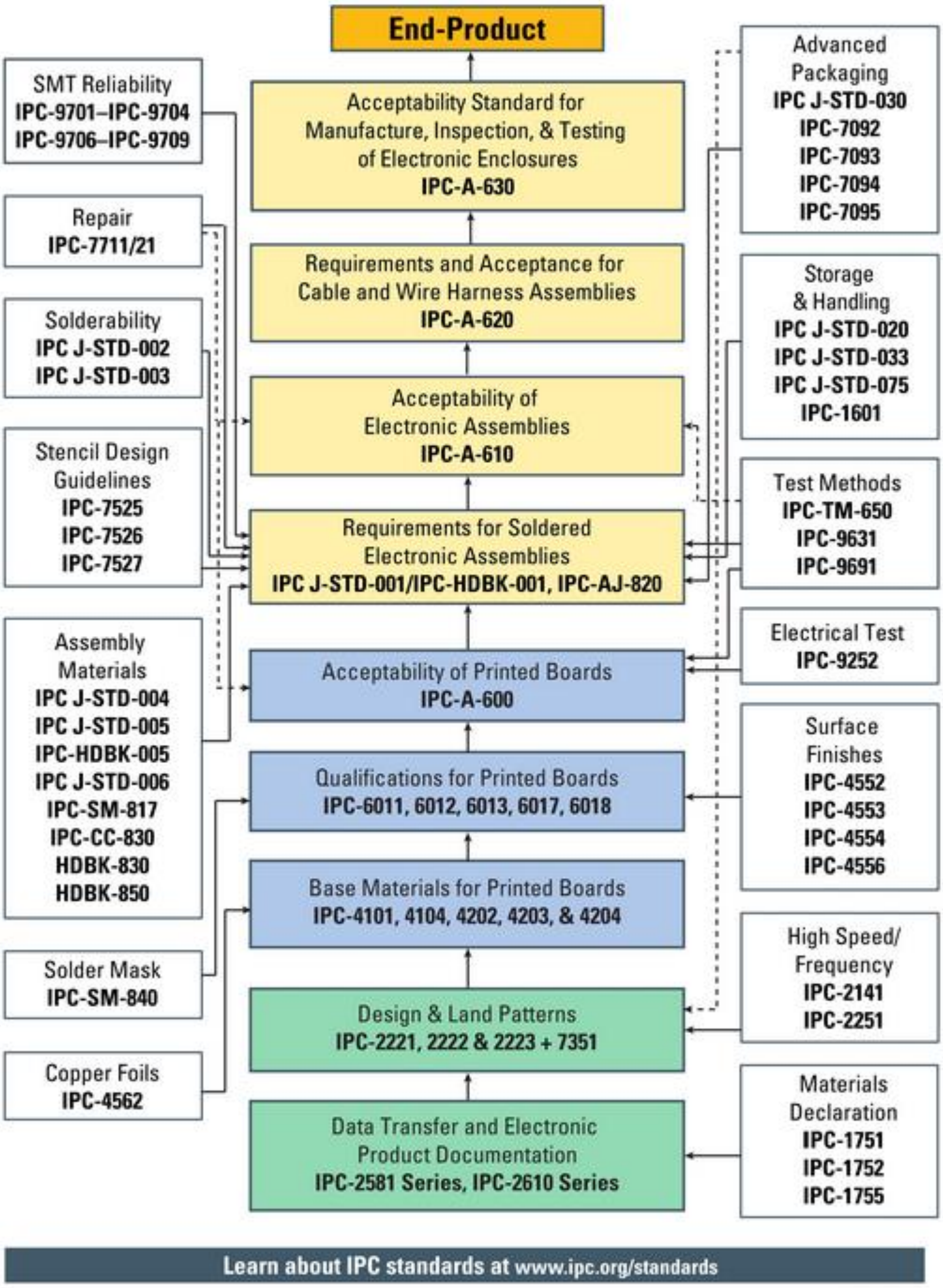


Figure 1 - IPC standards

Overall in IPC standards there is a lot of collected knowledge from electronics manufacturing companies for almost each of the individual steps of electronic products. Following the requirements and recommendations of IPC standards in organization and managing of the electronics manufacturing company allows ensuring effectivity of the processes and quality of the manufactured products.

One of the important documents for mount placement is IPC-9850A standard - Surface Mount Placement Characterization [3], with the help of which it is possible to identify the most important parameters of the equipment, such as accuracy and productive capacity of component installation. This way it will easier the decision to make in regards of equipment to be chosen for particular needs of manufacturing with respect to ratio between performance and quality.

1.4 Necessity to optimize manufacturing processes using mathematical models

Nowadays the right strategy for renewal, modernization or substitution of the manufacturing equipment can ensure high competitiveness level of the company for a longer period on the market. However, in order to receive successful results it is needed not only professionalism and experience of the personnel, but also use of complex mathematical models, which are able to predict the final result of decision to be made.

The first theory and development of techniques for the optimal allocation of resources was invented by Leonid Kantorovich, who was the founder of linear programming and in his works described possible ways how to organize and plan the manufacturing processes [4]. Next step was introduction to dynamic programming also known as dynamic optimization - a method for solving a complex problem by breaking it down into a collection of simpler subproblems, solving each of those subproblems just once, and storing their solutions - ideally, using a memory-based data structure. The next time the same subproblem occurs, instead of recalculating its solution, one simply looks up the previously computed solution, thereby saving computation time. Dynamic programming algorithms are often used for optimization. A dynamic programming algorithm will examine the previously solved subproblems and will combine their solutions to give the best solution for the given problem.

Mathematical modelling is one of the effective means to classify the effective performance of the company, which also includes identifying of the parameters and criteria for quantitative assessment. In the field of mathematical optimization, stochastic programming is a framework for modelling optimization problems that involve uncertainty.

Manufacturing company is a complex system, which requires continuous management control and monitoring of all the operations of all the production processes.. Implementation of a management system in the tough economic environment is the most important task of the head of the organization. Usage of the process approach, when the output of the production process at the same time is the input for the next, can help to look into the individual processes of the whole chain of manufacturing. Inputs and outputs define the boundaries of the process, ensure its interaction with other processes and create opportunities for changes in the process in order to improve the whole chain. It also gives the opportunity to simplify the overall management of the manufacturing process and its individual operations. Nowadays there are many tools and methods which help to identify weak areas and possible ways for improvement in the processes, some of them are described in the following chapters.

1.5 Methods and tools for quality optimization in manufacturing processes

1.5.1 SIX SIGMA

Six Sigma is a set of practices designed to improve manufacturing processes and eliminate defects. The core principle of the defect theory is that variation in manufacturing processes is the main cause for defects, and eliminating variation will help eliminate defects, which will eliminate the wastes associated with defects, saving money and increasing customer satisfaction. Variation is measured in terms of sigma values or thresholds. The threshold determined by Smith and agreed to by Motorola is 3.4 defects per million opportunities (3.4 DPMO), which is derived from sigma shifts from specifications.

Six Sigma relies in statistical control of a process. From requirements for the process it is possible to establish upper and lower specification limits (USL and LSL, respectively, see Figure 2). The target value will be in the middle of these two, and is called mean. These limits and the mean are fit to the normal distribution curve to achieve a statistical understanding of the process. The area under the curve means probability of variation from the mean.

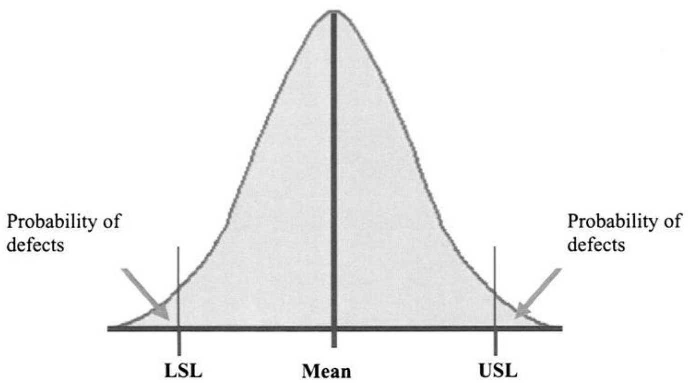


Figure 2 - A normal distribution curve with USL, LSL and Mean

After the process is in statistical control, the challenge is to get it to maintain its capability for longer periods of time. In short term, i.e. right after implementation, six-sigma is very reliable holding defects to 2 in a billion. After a while operator errors and machine wear etc. constitute a shift in the mean as large as 1.5 sigma. This distribution shift results in weakening of the process capability to 3.4 defects in a million in Six Sigma.

The idea of Six Sigma has appeared at Motorola in the 1970s, when senior executive Art Sundry was criticizing Motorola's bad quality [4]. Through this criticism, the company discovered the connection between increasing quality and decreasing costs in the production process. Motorola developed this new standard and created the methodology and needed cultural change associated with it.

Six Sigma was inspired by preceding improvement methodologies such as Quality Control, Total Quality Management and Zero Defects. Like its predecessors, Six Sigma assumes that continuous efforts for achieving stable and predictable results are important for business success; manufacturing processes have characteristics that can be measured and analysed.

In recent years, some practitioners have combined Six Sigma ideas with lean manufacturing to yield a methodology named Lean Six Sigma. Lean manufacturing is addressed to process flow and waste issues and Six Sigma focuses on variation and design. Six Sigma has evolved over time. It is more than just a quality system like TQM or ISO.

Introduction to Six Sigma

Six Sigma is a methodology focused on creating breakthrough improvements by managing variation and reducing defects in processes across the manufacturing process. Every company should be able to produce high quality products with low cost in order to successfully compete in the global market and satisfy customers' needs. Customers are the ones who decide if the quality is good or not, or if they will buy these products once again. For that reason, successful companies design their products and manufacture them based on customers' specifications. These desired parameters are called "target value". This target value can't be always reached in reality; products incline to giving a distribution with mean value different from targeted value. In order to be as close as possible to target value, quality analysis should be implemented, these different quality control methods can help producers to reach better level and help them develop their products in order to satisfy customers' requirements. One of the most widely used quality management methods is Six Sigma to improve quality. Six Sigma's aim is eliminating waste and inefficiency, desire to increase customer satisfaction. Moreover it is a structured approach to improving processes, lowering defects and reducing process variability, reducing costs and increasing profits.

Six Sigma is trying to prevent problems by building quality into the processes. Six Sigma is as well a method which is based on principle oriented on analysing causes of potential problems before they occur. In statistical terms, the variability (or sigma) of a nearly perfect process is so small that there are six standard deviations between the mean quality of the process and the quality level most customers expect of it. In practical terms, sigma is a measure of the number of times a process is defective, or fails, per million iterations or units of output. The greater the sigma number, the fewer the defects. The average product or process defect rate at most major companies is about four sigma, or more than 6000 defects per million. Six Sigma processes, by contrast, produce no more than 3.4 defects per million.

How does Six Sigma work (tools and techniques)

The primary focus of any Six Sigma project is bringing breakthrough improvements in a systematic manner by managing variation and reducing defects. At its core, Six Sigma revolves around a few key concepts:

- Critical to Quality: Attributes most important to the customer;
- Defect: Failing to deliver what the customer wants;
- Process Capability: What the process can deliver;
- Variation: What the customer sees and feels;
- Stable Operations: Ensuring consistent, predictable processes to improve what the customer sees and feels;
- Design for Six Sigma: Designing to meet customer needs and process capability.

The principle of Six Sigma is to attack causes of potential problems before they occur. This is of great value since correcting problems and redesigning processes afterwards is extremely costly and difficult. The method reveals the sigma level of different processes - either it is too low and important to improve or too high and too difficult to improve. To achieve a high standard deviation it is important to realize the effect of engineering design, material choice, process design and control strategy. Also, to keep Six Sigma successful continuously it is important to involve all of the organization, from raw material to packaging and shipping of the final goods.

Six Sigma projects follow two project methodologies, which have five phases each and bear the acronyms DMAIC and DMADV [5]:

- **DMAIC** is used for projects aimed at improving an existing business process.
- **DMADV** is used for projects aimed at creating new product or process designs.

The DMAIC project methodology has five phases (see Figure 3):

- **D**efine the problem or process goals in terms of key parameters on the basis of customer requirements. The objectives and scope of the project are defined. Relevant information about the process and customer are collected [6].
- **M**easure key aspects of the current process and collect relevant data or measure the current process performance in context of goals.
- **A**nalyze the current scenario in terms of causes of variations and defects. Determine what the relationships are, and attempt to ensure that all factors have been considered. Seek out root cause of the defect under investigation.
- **I**mprove the process or optimize the current process based upon data analysis using techniques such as design of experiments, Poka Yoke or mistake proofing, and standard work to create a new, future state process.
- **C**ontrol the future state process to ensure that any deviations from target are corrected before they result in defects.

Figure 3 - The DMAIC-method used in implementing Six Sigma

The DMADV project methodology, also known as DFSS ("Design For Six Sigma"), features five phases:

- **D**efine design goals that are consistent with customer demands and the enterprise strategy.
- **M**easure and identify CTQs (characteristics that are Critical To Quality), product capabilities, production process capability, and risks.
- **A**nalyze to develop and design alternatives, create a high-level design and evaluate design capability to select the best design.
- **D**esign details, optimize the design, and plan for design verification. This phase may require simulations.
- **V**erify the design, set up pilot runs, implement the production process and hand it over to the process owner.

Within the individual phases of a DMAIC or DMADV project, Six Sigma utilizes many tools that are also used outside of Six Sigma. It is extremely important to remember that Six Sigma is not just about product quality where only three products in a million are defective. It is about what is important or critical to the customer, whether internal or external. It is focuses on value in context of the customer and the market.

Past definitions of quality focused on conformance to standards, as companies strived to create products and services that fell within certain specification limits. The Six Sigma strategy broadens the definition of quality to include economic value and practical utility to both the company and consumer [7].

Methods, tools and techniques are important to the success of any Six Sigma project whether DFSS or DMAIC. Every stage of a Six Sigma project requires a mixture of these methods, tools and techniques. **Method** is a way of doing something in a systematic way. A **tool** provides a mechanical or mental advantage in accomplishing a task. A **technique** is a specific approach to efficiently accomplish a task in a manner that may not be immediately obvious. Most tools can be classified into two categories: process optimization tools, which enable teams to design more efficient workflows, and statistical analysis tools, which enable teams to analyze data more effectively.

Here is an overview of some of the most important tools:

- Statistical process control is one of the most important applications of the statistics. It is covering variety of tools and it can be considered that seven Ishikawa tools, also known as seven quality tools, are among most famous and useful tools**. Seven Ishikawa tools** are:
    - **Cause and Effect Diagrams** - is a visual tool that logically organizes possible causes for a specific problem or effect by graphically displaying them in increasing detail. It is sometimes called a fishbone diagram because of its fishbone shape. This shape allows the team to see how each cause relates to the effect. It then allows you to determine a classification related to the impact and ease of addressing each cause.
    - **Pareto Charts** - is a graphic tool that prioritizes a list of variables or factors based on impact or frequency of occurrence. This chart is based on the Pareto principle, which states that typically 80% of the defects in a process or product are caused by only 20% of the possible causes.
    - **Flow Charts -** is a visual representation of a process. It is not statistical, but is used to piece together the actual process as it is carried out, which quite often varies from how the process owner imagines it is.

Seeing it visually makes identifying both inefficiencies and potential improvements easier.

- **Check sheet** - are used to capture data in a manual, reliable, formalized way so that decisions can be made based on facts. As the data is collected, it becomes a graphical representation of itself. Areas for improvement can then be identified, either directly from the check sheet, or by feeding the data into one of the other seven basic tools.
- **Scatter Plots** - is used to identify whether there is a relationship between two variables. It does not prove that one variable directly affects the other, but is highly effective in confirming that a relationship exists between the two. It is a graphical more than statistical tool. Points are plotted on a graph with the two variables as the axes. If the points form a narrow "cloud", then there is a direct correlation. If there is no discernible pattern or a wide spread, then there is no or little correlation.
- **Control Charts** - are time-ordered graphical displays of data that plot process variation over time. Control charts are the major tools used to monitor processes to ensure they remain stable. Control charts are characterized by a centreline, which represents the process average. Upper and lower control limits, which define the area three standard deviations on either side of the centreline. Control limits reflect the expected range of variation for that process. The type of chart to use depends upon the type of data to be measured; i.e. whether it is attributable or variable data. The most frequently used Control Chart is a Run Chart, which is suitable for both types of data. They are useful in identifying trends in data over long periods of time, thus identifying variation.
- **Histograms** - are a form of bar chart. They are used to measure the frequency distribution of data that is commonly grouped together in ranges or "bins". Most commonly they are used to discern frequency of occurrence in long lists of data.

The seven basic tools of quality can be used singularly or in tandem to investigate a process and identify areas for improvement, although they do not all necessarily need to be used. If a process is simple enough – or the solution obvious enough – any one may be all that is needed for improvement. They provide a means for doing so based on facts, not just personal knowledge, which of course can be tainted or inaccurate. Ishikawa advocated teaching these seven basic tools to every member of a company as a means to making quality endemic throughout the organization [8].

- Sometime later were developed the seven **new quality control tools**, often called the seven management and planning (MP) tools, or simply the seven management tools (New tools are considered to be more relational and network oriented, are taking more practice to develop proficiency):
    - **Affinity diagram** - organizes a large number of ideas into their natural relationships. The use of this tool is based on the understanding that time invested in planning will produce remarkable dividends as the generated ideas and plans are acted upon and implemented.
    - **Relations diagram** - shows cause-and-effect relationships and helps analyzing the natural links between different aspects of a complex situation. Can address problems with a complex network of causes and effects.
    - **Tree diagram -** expands a purpose into the tasks required to accomplish it. Tree diagram breaks down broad categories into finer and finer levels of detail, helping to move thinking step by step from generalities to specifics. This diagram is a tool that is used to break any concept (such as a goal, idea, and objective) into subcomponents, or lower levels of detail. Graphically shows any broad goal broken into different levels of detailed actions.
    - **Matrix diagram** - shows the relationship between two, three or four groups of information and can give information about the relationship, such as its strength, the roles played by various individuals, or measurements.
    - **Matrix data analysis** - arranges a large array of numbers so that they may be visualized and comprehended easily. One of the most rigorous, careful and time-consuming of decision-making tools, a

prioritization matrix is an **L-shaped matrix** that uses pair wise comparisons of a list of options to a set of criteria in order to choose the best option.

- **Arrow diagram** - establishes the most suitable daily plan. It is a network of lines that connects all of the elements related to plan execution. Arrow diagram shows the required order of tasks in a project or process, the best schedule for the entire project, and potential scheduling and resource problems and their solutions.
- **Process decision program chart** (PDPC) - maps out all contingencies when moving from statement of purpose to its realization, systematically identifies what might go wrong in a plan under development.

The seven new tools display information in intuitively helpful way, promote non-linear thinking, can be used with “old” tools.

- **The rest of the tools are: 5S** – The 5S idea is Sort, Straighten, Shine, Standardize and Sustain in every manufacturing process. The list of these words describes how to organize a work place for efficiency by identifying and storing used items, maintaining the area and sustaining the new order.
- **Analysis of Variance** (ANOVA) – is a mix of statistical models in which the variance is partitioned into components attributable to different sources of variation. ANOVA provides a statistical test and brings an understanding whether or not the means of several groups are all equal and generalizes t-test to more than two groups.
- **Brainstorming** – is a technique to systematically generate ideas usually to handle a challenging situation, from a group of people. Some of the challenges include problem solving, new design or new product development.
- **Capability Indices/Process Capability** – the capability analysis output includes an illustration of the data and several performance statistics. The plot is a histogram with the performance standards for the process expressed as upper and lower specification limits (USL and LSL).

- **Design of Experiments** (DOE) – is a tool that si giving information about how factors alone and in combination, affect a process and its output. This approach often requires a great many runs and cannot capture the effect of combined factors on the output.
- **Failure mode and effects analysis** (FMEA) – a method to identify ways a process can fail, estimate the risks of those failures, evaluate control plan, and prioritize actions related to the process.
- **Poka Yoke** – mistake-proofing devices prevent defects by preventing errors or by predicting when errors could occur.
- **Process Mapping** – is a tool that provides structure for defining a process in a simplified manner by displaying the steps, events and operations that make up a process.
- **QFD/House of Quality** – a methodology that provides a flow down process from the highest to the lowest level. QFD is a prioritization tool used to show the relative importance of factors rather than as a transfer function.
- **Risk Management** - is a methodology used to identify, plan and analyze risks.
- **Simulation** – is a powerful analysis tool used to experiment with a detailed process model to determine how the process output will respond to changes in its structure, inputs, or surroundings.
- **SIPOC** – is a high level picture of the process that depicts how the given process is servicing the customer. It is an acronym for Suppliers-Inputs-Process-Outputs-Customers.

If to take into account DMAIC stages of the process together with the types of activities the project team will carry out, is possible to compile an overview table, which will help to define the manufacturing process in best way for better understanding and discovering possible mistakes or items to be improved. An illustrative form of such a table can be as following (the tools and techniques listing is by way of example and are not exhaustive) (see Table 1):

Step	Purpose	Activities	Tools and Techniques
Define	To define the problem, develop a clear view based on real problem	• Identify improvement opportunity • Develop charted • Define critical customer requirements • Map processes	• Charter • Milestone plan • Process maps • Affinity diagram
Measure	To understand the baseline and current levels of performance	• Identify measures • Develop operational definitions • Develop and implement measurement plan • Collect other baseline information	• Detailed process mapping • Measurement plan • Critical to Quality requirements (CTQ) • FMEA analysis
Analyze	To develop, select and understand their effect of the process	• Identify root causes • Determine true sources of variation • Process control and capability • Plot and analyze data • Determine sigma score	• Statistical process control • Fish bone diagrams • Cause and effect diagram • 5 whys • Pareto chart • Histograms
Improve	To develop, select and implement the best solutions	• Generate solution ideas • Evaluate and select solutions • Develop process map for solutions • Initiate measure and evaluate pilot	• Process maps • Brainstorming • Affinity diagrams • Solution screening • Control charts
Control	To ensure the solutions are embedded, that the process has robust control	• Verify reduction in variation and sigma score • Develop standard practices • Monitor performance • Recommend future plans • Identify next steps and remaining opportunities	• Control plan • Statistical process control

Table 1 - An example of realizing DMAIC using some of the Six Sigma tools and techniques

Benefits of Six Sigma

Six Sigma is a business strategy which is seeking to identify and eliminate causes of errors or defects or failures in business processes by focusing on outputs that are critical to customers. The fundamental objective of the Six Sigma methodology is the implementation of a measurement-based strategy that focuses on process improvement and variation reduction.

There are numerous benefits of Six Sigma as a way to address issues and problems. Among the benefits of Six Sigma is the decrease in defects that are allowed to reach the customer. Other benefits of Six Sigma include:

- Focus on customers.
- Reduced cycle time.
- Less waste.
- Data based decisions - Six Sigma emphasizes the importance of data and decision making based on facts and data rather than assumptions and hunches. Six Sigma forces people to put measurements in place.
- Time management - For more productive life personal time management and time management skills should be used on a daily basis.
- Sustained gains and improvements.
- Systematic problem solving - Six Sigma methodology of problem solving integrates the human elements (culture change, customer focus, belt system infrastructure, etc.) and process elements (process management, statistical analysis of process data, measurement system analysis, etc.) of improvement [9].
- Data analysis before decision making - Six Sigma utilizes the concept of statistical thinking and encourages the application of well-proven statistical tools and techniques for defect reduction through process variability reduction methods (e.g.: statistical process control and design of experiments)
- Improved customer relations.
- Assure strategic planning.
- Reductions of incidents.
- Understanding of processes - Six Sigma methodology utilizes the tools and techniques for fixing problems in business processes in a sequential and

disciplined fashion [9]. Each tool and technique within the Six Sigma methodology has a role to play and when, where, why and how these tools or techniques should be applied is the difference between success and failure of a Six Sigma project.

- Design and redesign products/services.
- Develop leadership skills - Six Sigma strategy places an unprecedented importance on strong and passionate leadership and the support required for its successful deployment.
- Improve quality – reduce defects and errors
- Improve reliability of products and processes
- Reduce cost of operations
- Improve productivity
- Improve customer satisfaction
- Improve profits

Six Sigma enables organizations to become more effective and efficient. Organizations using the Six Sigma Management System improve their processes, efficiency, products, services and customer experience.

Weak points of Six Sigma

Just as any other quality management initiatives, Six Sigma has its own limitations. The following are some of them, which create opportunities for future research:

- Lack of data – it can happen, that there is no data available to begin with, so gathering the necessary data can take the largest proportion of the project time.
- Right selection and prioritization of projects – it is a critical success factor of a Six Sigma program. Just few tools are available for prioritizing projects and this should be the major issues for research in the future.
- Impossibility of defects measuring – it is not always possible to define a defect statistically. The statistical definition of Six Sigma is 3.4 defects or failures per million opportunities. However, a defect can be defined as anything

which does not meet customer expectations or needs (for example, lack of training people, etc.) [9].

- Sigma shift – assumption of 1.5 sigma shift for all business processes does not make much sense. This particular issue should be dealt with extra caution as a small shift in sigma could lead to erroneous defect calculations.
- Overselling of Six Sigma – there are too many consulting firms which are offering Six Sigma, nevertheless their knowledge in this area can be poor.

In spite of some of the disadvantages Six Sigma is likely to remain one of the key initiatives to improve management process.

Future of Six Sigma

Six Sigma provides an effective means for deploying and implementing statistical thinking, which is based on the several principles that all work occurs in a system of interconnected processes, that variation exists in all processes and that should exist and understanding of the data which explains variation in processes. The mentioned principles of statistical thinking within Six Sigma are robust and therefore it is fair to say that Six Sigma will continue to grow in the upcoming years. The general focus of Six Sigma should be on improving overall management performance, not just pointing and counting defects. Integrating and comparing principles and characteristics of Six Sigma with Total Quality Management , Lean Production, ISO9001 and other methods are all part of the quality community's effort to maximize the positive effect of the Six Sigma method.

1.5.2 LEAN SIX SIGMA

Nowadays Lean Production and Six Sigma are starting to be widely spread, but they are used mostly separately. As to mention, Lean is a set of principles, practices and tools aimed at creating precise customer value. Lean can be applied to all aspects of an organization, from product development and provision through administration and finance to customer services and support. The goal of Lean is to create high quality, defect free products and services at all stages of the customer experience, whilst using less capital, space and effort to produce this. From first point of view the goals are pretty similar to Six Sigma methodology. However, Six Sigma is more a statistical term used to measure how far a given process deviates from perfection. Organizations use Six Sigma to identify and eliminate costs that provide no value to customers. They analyze their processes to find out where and how defects occur, measure them and eliminate the problem areas. The idea is that, if you can measure the number of defects there are in a process, you can then systematically attempt to eliminate them to get as close to zero defects as possible. The generally accepted definition of the Six Sigma benchmark is 3.4 defects per million opportunities for each product or service transaction.

As a name suggests, Lean Six Sigma is a combination of Lean methods and Six Sigma approaches. Lean Six Sigma builds on the knowledge, methods and tools coming from decades of operational improvement and research. However, Lean Six Sigma’s goal is growth, not just cost-cutting. Its aim is effectiveness, not just efficiency. In this way, a Lean Six Sigma approach drives organizations not just to do things better but to do better things.

The Lean Manufacturing methodology is used by an organization's leaders and engineers to fine-tune its daily operations, while the Six Sigma methodology is used to support innovations in the production process. Thus, while lean manufacturing is able decrease production waste, Six Sigma is able to implement procedures to increase product quality. As a result, Lean Six Sigma allows managers to effectively address issues of speed, quality, and cost. Rather than to either eliminate steps that may appear wasteful or spend months testing a variety of innovative options, Lean Six Sigma balances the worth of each of the two methodologies from which it originates.

As an example of some tools and techniques used in each of the technologies the following table can be a good demonstration (see Figure 4):

Lean	
Philosophies	**Example tools**
Emphasis on eliminating waste and improving flow	**Value stream map** - analyze and design the flow of materials and information
Quickly identify and implement changes	**Kaizen event** - a focused effort to make an improvement.
Focus on customer needs, not company capabilities	**CTQ** (critical-to-quality) - discomposure of requirements into more easily quantified requirements
Test before implementing changes	**PDSA cycle** – plan–do–check–act

Do the right activities
Speed and efficiency – make it faster

Six Sigma	
Philosophies	**Example tools**
Emphasis on reducing defects and variation	**Control chart**
Methodically make improvements and solve the problem	**DMAIC**
Focus on root causes, not symptoms	**Cause-and-Effect diagram**
Understand process linkages	**SIPOC diagram**

Do the activities right
Precision and accuracy – make it better

Lean efficiency enables Six Sigma effectiveness
(faster learning and implementation)

Six Sigma effectiveness enables Lean efficiency
(fewer defects = less rework time)

Figure 4 - Example tools of Lean Six Sigma

The fusion of Lean and Six Sigma is required because [10]:

- Lean cannot bring a process under statistical control.
- Six Sigma individually used cannot dramatically improve process speed or reduce invested capital.

Lean Six Sigma concepts are extremely powerful in improving the quality and speed of all types of transactional processes (e.g. product development, financial resources, sales, etc.), which should also be improved in manufacturing companies, as they enable the manufacturing process. That is why so important to look on the every particle which can cause some difficulties in the future fulfilling of the process, especially such accuracy is needed in electrical engineering. Lean Six Sigma is an integrated and balanced combination of the speed and variation reduction power of both Lean and Six Sigma to achieve business management process full optimization.

Creating a system for process improvement in electronics production, which combines suitable features from Lean and Six Sigma methods can significantly improve lead time of the manufacturing process, increase the quality level of the output products and sustain the continuous improvement with the usage of latest technologies and innovations.

Lean Six Sigma is also a structured methodology that uses a set of management and statistical methods to optimize business processes. In order to map the Lean principles to the Six Sigma methodology, i.e. DMAIC process in particular, it is essential to understand how each phase of DMAIC was used to execute a full scale Lean design effort (Table 2 and Figure 5):

Phase	Tool	Deliverables
Define	Product Family Matrix	Project scope
		Define the value
		Define value boundaries
	SIPOC	Project start
		Project end
		Duration
		Project goal
		Expectations
	FMEA	Identify risks and gaps
	Value Stream Mapping	Define Value stream
Measure	Value Stream Mapping	Identify major sources of waste
		Layout the VSM timeline
Analyze	VSM analysis	Determine total cycle time
		Identify flow interruptions
		Identify bottlenecks
	Gap analysis	Generate future state VSM
Improve	Solution matrix	Consolidate improvements
	FMEA	Prioritize improvements
	Action Plan	Implementation plan for future improvements
	Metrics dashboard	Improvements summary (before, current, target)
	5S	Visual workplace applications
	Work Standardization	
Control	Control charts	Finalize 5S Sustainability
	Mistake proofing	Finalize Visual Workplace
	Control plan	

Table 2 - Lean principles on DMAIC process

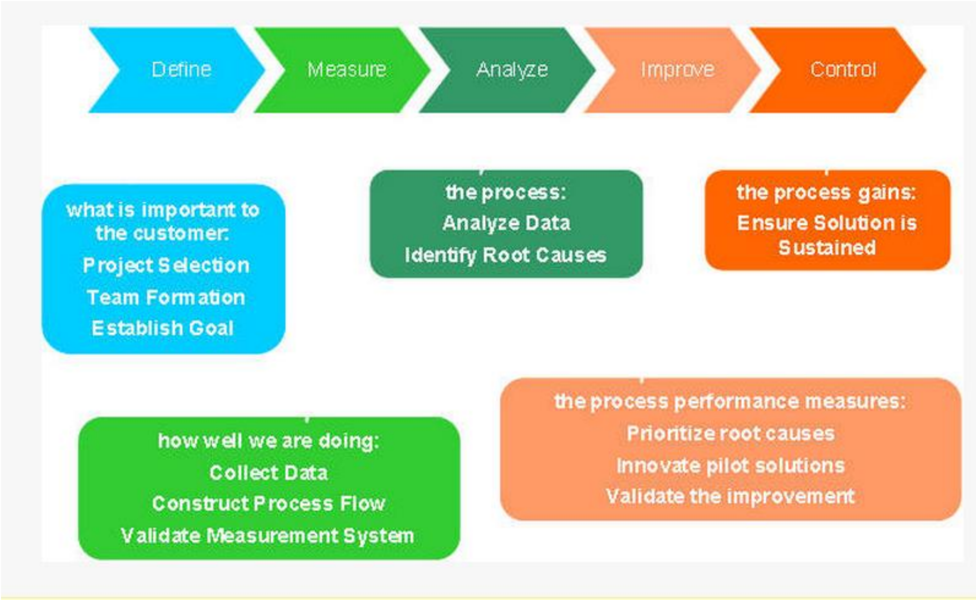


Figure 5 – Lean Six Sigma DMAIC process

Following each of the phases and its deliverables for chosen tools thus it is possible to analyze and optimize the manufacturing process.

1.5.3 FUZZY LOGIC

A logic which is based on the two truth values True and False is not describing completely human reasoning. Fuzzy logic is using the whole interval between 0 as False and 1 as True to describe the human reasoning. And as a result fuzzy logic is being applied in control engineering. The advantage of a fuzzy logic system is an approach which incorporates both numerical results from a previous solution or simulation and the scheduling expertise from experiences and observation.

Qualitative measures often need to be translated into quantitative measures. For example, the qualitative measure of customer responsiveness can be translated into the quantitative measures of fill rate, product lateness, and lead time [13].

Fuzzy inference is the process of formulating the mapping from a given input to an output using fuzzy logic (major stages being fuzzification, rule evaluation and aggregation, and defuzzification). The mapping of defuzzified results onto the problem situation then provides a basis from which decisions can be made. There are two types of fuzzy inference systems that can be implemented: Mamdani-type and Sugeno-type [14].

Many sets in the world that surrounds us are defined by a non-distinct boundary [15]. As for process control and quality control in manufacturing fuzzy logic and fuzzy relations are the most important in order to understand how fuzzy rules work. A fuzzy set is a development of the mathematical concept of a set; however a grade of membership has been introduced, such that the transition from membership to non-membership is gradual rather than abrupt. The grade of membership for all its members thus describes a fuzzy set. And an item’s grade of membership is a number between 0 and 1. The determination of the grade of membership does not have a formal basis; it is a subjective measure that depends on the context.

Fuzzy mathematics is a broad field touching on nearly all traditional mathematical areas. Fuzzy sets were first proposed in the early 1960s by Zadeh [15] as a general model of uncertainty encountered in engineering systems. His approach emphasized modelling uncertainties that arise commonly in human thought processes. Although fuzzy mathematics arose and developed from the systems area, it perhaps belongs best to in the realm of Artificial Intelligence (AI) techniques as an interesting form of knowledge representation.

Fuzzy systems are rule-based systems that are constructed from a collection of linguistic rules. Some of the most useful capabilities and features provided by modelling in fuzzy set approaches are:

- Representation of methods for natural language statements;
- Integration between logical and numerical methods;
- Models for soft constraints;
- Models for resolving multiple conflicting objectives.

Subjective assessments of the above mentioned uncertainties are needed to reach a decision [3]. These uncertainties can be separated into two groups:

1. Measurements and models of the system (equipment failure modes, modelling errors, predicted demands, system dynamics, etc.)

2. Constraints and objectives arising from decision-making process (assessment of customer satisfaction, operational limits, power quality objectives, stability limits).

There are four steps to follow to design a fuzzy model, among them are:

1. Definition of the model function and operational characteristics

The goal is to establish the architectural characteristics of the system and also to define the specific operating properties of the proposed fuzzy system, to the number and ranges of input and output that will be required. It also reinforces the input-process-output design step.

2. Definition of the control surfaces

Each control and solution variable in the fuzzy model is decomposed into a set of a fuzzy regions. These regions are given a unique name, called labels, within the domain of the variable.

3. Definition of the behaviour of the control surfaces

This step involves writing the rules that tie the input values to the output model properties. These rules are expressed in natural language with syntax such as:

IF<fuzzy proposition>, **then**<fuzzy proposition> that is, IF, THEN rule, where fuzzy proposition are “x is y” or “x is not y” x is a scalar variable, and y is a fuzzy set associated with that variable. Generally the number of rules a system requires is simply related to the number of control variables.

4. Selection of a method of defuzzification

It is the way to convert an output fuzzy set into a crisp solution variable. The two most common ways are:

- The composite maximum;
- Calculation of the concentration.

Once the fuzzy model has been constructed, the process of solution begins. The model is compared against known test cases to validate the results. When the results are not as desired, changes are made either to the fuzzy set descriptions or to the mappings encoded in the rules.

PCB manufacturing process is a complex process with a lot of different operations involved as well as many components, which work in sequence. Important is to cope with the complexity of the system and to make the system more reliable, efficient with the high standard of output product. These are reasons to use fuzzy notations, which can handle uncertainties and essential for a human expert's knowledge acquisitions. Fuzzy set theory was developed to improve the oversimplified model, thereby developing a more robust and flexible model in order solve real-world complex systems involving human aspects. Fuzzy set theory can help the decision maker not only to consider the existing alternatives under given constraints (optimize a given system), but also to develop new alternatives (design a system).

1.5.4 LEAN SIX SIGMA AND FUZZY PRINCIPLES

The production parameters from manufacturing processes are statistical variables and therefore they have some dispersion. In order to create a reliable and flawless production line is important to consider many aspects, including such as continuous improvement of existing processes, calculating the defect ratio of the output products, analyzing the existing lead times of processes, where the improvement would be possible or needed and etc.

Fuzzy logic is defining the framework through a compact linguistic rule base. It has the ability to simultaneously consider multiple criteria and to model human experience in the form of simple rules. The advantage of the fuzzy logic system approach is that it incorporates both numerical and linguistic variables.

Applying Lean Six Sigma methodologies on different stages can help to benefit on many process levels: to evaluate the efficiency of the chosen manufacturing line, make the manufacturing processes run faster and more stable with less failures and can help to create a systematic approach in all the mentioned benefits above. Fuzzy approach and Fuzzy logic based systems with their capability to deal with incomplete information, imprecision, and incorporation of qualitative knowledge show a great potential for applications in electrical engineering systems as well as serve as a good basis for measuring effectiveness of chosen methods. Combining different type of quality methods and fuzzy mathematical tools will provide a broader view on the performed process and will help to create an understanding where it can be improved, and thus control and improve the quality.

1.6 Conclusion for chapter 1

The electronics market analysis has shown and confirmed the tendency to reduce size of electronic components and growth of the requirements for their functionality, which leads to rapid aging of existing technologies and equipment and as a result leads to inability to produce competitive products. Therefore there is a need in development of new technologies and renewal of existing company resources for electronics manufacturing.

Usage of innovative technologies will help to raise the level of competitiveness as well as raising the effectiveness of manufacturing process and quality of manufactured products.

Several control methods were described in order to show possible ways how to analyze the manufacturing process, determine weak pointes or possible failures which are occurring in the system as well as work on the steps to make the system working more stable, seamless and faster.

2 EFFECTIVENESS CRITERIA FOR IMPLEMENTING INNOVATIVE TECHNOLOGIES IN PCB ASSEMBLY PROCESS

2.1 Preconditions for improvement of PCB assembly process

Electronics is the branch of science, engineering and technology that deals with electrical circuits involving active electrical components such as vacuum tubes, transistors, diodes and integrated circuits. The role of information technology in production networks in developing countries cannot be assessed without an analysis of the profound changes. Information technology evolves every year and it is seen that with every following year there are some innovations appearing in all the fields. An electronic component is any physical entity in an electronic system used to affect the electrons or their associated fields in a desired manner consistent with the intended function of the electronic system. Components are generally intended to be connected together, usually by being soldered to a **printed circuit board** (PCB), to create an electronic circuit with a particular function.

The printed circuit board manufacturing process is a difficult and complex series of operations to make a printed circuit board. Printed circuit boards are insulating boards with conductive layout that connects the assembled electronic components. There are three basic varieties of printed circuit boards: single-sided, double-sided, and multi-layered. Printed circuit boards are employed in the manufacturing of business machines and computers, as well as communication, control, and home entertainment equipment.

Specifics of PCB production:

A printed circuit board (PCB) mechanically supports and electrically connects electronic components using conductive tracks, pads and other features etched from copper foils with thickness of 8 to tents of micrometres laminated onto a non-conductive substrate. Components – capacitors, resistors, inductors and other active devices – are generally soldered on the PCB. Advanced PCBs may contain components embedded in the substrate [12].

PCBs can be single sided (one copper layer), double sided (two copper layers) or multi-layer (outer and inner layers). Multi-layer PCBs allow for much higher component density.

After the printed circuit board is completed, electronic components must be attached to form a functional printed circuit assembly. In assembly the bare board is populated with electronic components to form a functional circuit. In through-hole technology, the component leads are inserted into the holes, whose inner wall is metallized, the holes are surrounded by conductive pads. The holes secure components to a given point and sometimes also serve to connect the conductive layers on different surfaces of the insulating board. In surface-mount technology (SMT), the component is placed on the PCB so that the pins line up with the conductive pads or lands on the surfaces of the PCB; solder paste, which was previously applied to the pads, holds the components in place before the reflow process and the solder holds the components in place after it. If surface-mount components are applied to both sides of the board, the bottom-side components are glued to the board. In both through-hole and surface mount, the components are then soldered.

There are a variety of soldering techniques used to attach components to a PCB. High volume production is usually done with machine placement and bulk wave soldering, vapor soldering or soldering in reflow ovens, but skilled technicians are able to solder very tiny parts by hand under a microscope, using tweezers and a fine tip soldering iron for small volume prototypes. Some parts may be extremely difficult to solder by hand.

The PCB manufacturing process is a complex sequence of many operations, therefore it is important to follow many instructions to get a non-defective production or bring the manufacturing to a level of minimum losses.

Analysis and modelling of PCB production:

Implementation of technological innovations requires careful and detailed analysis of manufacturing processes, based on mathematical modelling. This objective is important in order to evaluate the effectiveness of company activities.

Modelling is meant to substitute the real analyzed object (process, system, etc.) with its model (abstract object). However, the model imitates such properties and characteristics of real object, which are relevant in order to achieve the goal of modelling. There are experiments conducted on the model and research, on basis of which there are conclusions made about the real object properties.

Main objectives for estimation of effectiveness of company activity are determination of the current state of manufacturing processes and identifying main factors, which are influencing on the current state. Based on the obtained results of the evaluation the following strategy is being determined and the decision how to distribute the resources of the enterprise is being concluded.

The prerequisites for improvement of manufacturing processes in electronics field are constant growth of different technologies as well as growth in requirements for quality control and quality of the output products. The growth of technologies and complexity of design leads to increase of usage of more different components thus makes the manufacturing process more expensive.

Therefore all such complications is important to analyze in order to collect the information about real state of the company, identify weak points as well as strong ones and improve them even more with the continuous improvement, innovation technologies and focus on quality control.

Optimization of PCB manufacturing process is realized with the help of implementation of innovation technologies as well as analysis based on modern methods of quality control such as six sigma, lean production and mathematical modelling using fuzzy technologies. Efficiency criteria for implementing innovation technologies for PCB manufacturing process has been introduced based on IPC standards, e.g. in IPC-A-610 standard - a document indicating various characteristics of the board and/or assembly as appropriate relating to desirable conditions that exceed the minimum acceptable characteristics [20].

Standard IPC-A-610 reflect three classes, which are describing criteria of quality for electronic equipment: general electronic products, dedicated service electronic products and high performance electronic products. This document consists of such parts as hardware installation, wire bundle securing, wire crossover, soldering and soldering acceptability, terminal connections including edge clip, swaged hardware and lead and wire placement, insulation, through-hole technology including component mounting, component securing and supported holes, surface mount assemblies including chip components and components damage and parts for PCB and assemblies such as laminate conditions and marking, coatings and etc.

Meeting the requirements of IPC-A-610 standard helps to ensure high quality products, based on the use of known technologies assembly and installation of electronic products.

2.2 Determination of acceptance criteria and effectiveness factors

Defining some certain criteria usually takes place on the basis of the specific conditions of production and the accumulated experience in the field. The criteria should be comprehensive and quantifiable, in such a case it will fully reflect the actual state of the studied model, and the decision-maker will be able to use it.

In order to correctly determine the acceptance and effectiveness criteria for some particular manufacturing process, it is important to identify the goal of the research. In case if the goal is the increase in productivity, then the criteria are to increase the capacity and output of existing equipment. This thesis is describing the possible ways how to improve the quality of manufacturing processes with the help of innovation technologies, different methods of statistical tools and fuzzy logics. Therefore one of the main criteria is effectiveness factor of innovation technologies implementation, which can be determined by several sub factors.

In order to choose the correct criteria, it is important that these criteria will reach the expected goal. Taken into consideration this fact, the overall effectiveness factor ($F_{overall}$) can be divided in the following sub factors:

- Factor for minimizing the lead time of the manufacturing process (F_m);
- Defect factor (F_d);
- Product manufacturing quality factor (F_q);
- Factor of economic efficiency (F_e);
- Factor of staff skill qualification (F_s);
- Factor of automatization (F_a).

For each of these factors there are several parameters which are determining them, such as (see Table 3):

Factor for minimizing the lead time of the manufacturing process	**Defect factor**	**Product manufacturing quality factor**	**Factor of economic efficiency**	**Factor of staff skill qualification**	**Factor of automatization**
Time to control the PCB blanks	Mechanical defects	Precision of component placement on PCB	Profit	Theoretical preparation	Level of automatization of production
Time to plate the lead solder paste	Defects of material of PCB	Connection strength	Labour costs	Practical experience	Amount of staff involved in production
Time to mount the chip-components	Defect of component placement on PCB (polarity, existence or absence of components)	Degree of homogeneity of solder joint	Intensity of the usage of the equipment	Motivation	Time to setup equipment for new batch of products
Time to solder in reflow oven		Precision of solder paste application	Profitability of production		
Time to control the readiness of PCB		The degree of filling of the cell stencil of solder paste			

Table 3 - Individual factors and parameters for automatic PCB manufacturing process

For quantitative assessment for the individual factors it is necessary to develop mathematical model for evaluating the effectiveness of the implementation innovation process for PCB assembly. This will allow identifying the effectiveness of the whole technological system. The mathematical representation of the overall effectiveness factor is:

$$F_{overall} = \sum_{i=1}^{n} Fi \ ,$$

where $\mathbf{F_{overall}}$ is the overall factor to identify effectiveness of implementing innovation technologies; $\mathbf{F_i}$ is the individual factor and **i** - is the amount of individual factors.

For the electronics manufacturing the most important and technically complex process is the PCB assembly process. Taken it as an example, it is possible to subdivide it into individual operations and define complex metrics which can help minimizing the duration of the overall lead time of PCB assembly process.

The PCB assembly process consists of several operations (P1 – P5):

- Input control of PCB blanks (P1);
- Plating of the lead solder paste (P2);
- Mounting of chip-components (P3);
- Mass soldering (P4);
- Quality control of the assembly process (P5).

Input control of PCB blanks

The input control of PCB blanks (P1) is needed in order to control the possible defects, as well as suitability of the PCB boards to be loaded into automatic production. During the entry check there are several acceptance criteria, which are presented in Table 4.

Input parameters	**Acceptance criteria**	**Output parameters**
Presence of mechanical defects and defects during the PCB manufacturing (holes, etc.)	Visual control	External appearance of PCB board (PCB shall comply with IPC-A-600 [21] and IPC-A-610 requirements [22])
Flatness (bow and twist)	Measure the flatness (IPC-TM-650, method 2.4.22 [23])	Bow and twist values should not exceed 0.75% according to IPC-2221A, 5.2.4 [24]
Size (length, width)	Measurement of size	Precision of PCB size (according to IPC-2221A shall be within +/-0.4mm)
Dielectric constant	Stripline Test for Permittivity and Loss Tangent (IPC-TM-650 2.5.5.5)	The dielectric constant of PCB board (shall meet the requirements of the customer)

Table 4 – PCB parameters for input control

The operation of input control allows checking if the PCB blanks are in accordance with technical documentation and standards for their further appliance in the manufacturing process. For the input control there is the following type of equipment being used (table 5):

Acceptance criteria	Equipment
Visual control	- Control table - Magnifying glass
Measure the flatness (IPC-TM-650, method 2.4.22 [23])	- Control table - Micrometer
Measurement of size	- Control table - Ruler - Micrometer
Stripline Test for Permittivity and Loss Tangent (IPC-TM-650 2.5.5.5)	- Device for measuring the dielectric constant

Table 5 – Type of equipment for input control

In order to reduce the time for input control, it is necessary to define the parameters and their mathematical interpretation:

$$F_{m1} = \frac{F_{m1before}}{F_{m1after}} * M_{F_{m1}},$$

where

F_{m1} - parameter representing the overall time for input control;

$F_{m1before}$ - quantitative parameter before applying the innovation or improvement technologies;

$F_{m1after}$ - quantitative parameter after applying the innovation or improvement technologies;

$M_{F_{m1}}$ - weighting factor.

Application of the lead solder paste

After the operation of input control there is an application of the lead solder paste following. Let us take a case when the lead solder paste is applied with the help of automatic jet printer. The template is set by screen printing to motive of the board and solder paste is applied through the holes by use of wipers. Once the template tears off the board the solder paste stays ready to lay components. This process unlike manual soldering ensures consistency and saves time. However in order even more to reduce the time, the speed of template moving can be increased. Parameters, influencing on the soldering phase, are shown in Table 6.

Input parameters	Processes	Output parameters
External appearance of PCB board (shall meet the requirements of IPC-A-600G and IPC-A-610D)	Positioning of PCB board	Periodicity of alignment
Bow and twist values should not exceed 0.75% according to IPC-2221A (can vary depending on equipment)	Positioning of template on PCB board	Precision of placement
Precision of the size of PCB	Applying of solder paste	Steadiness of solder paste form (shall create correct geometrical forms)
The dielectric constant of PCB board (shall meet the requirements of the customer)	Tearing off the template from PCB board	Filling of the template with the solder paste

Table 6 – Parameters of lead solder paste process

At this stage jet printers for template printing are being used, for which the main parameters are the following:

- Flexibility to adapt to the new type of products;
- Periodicity of alignment with 6 sigma calculation;
- Precision of placement with 6 sigma calculation.

The mathematical interpretation for minimizing the time of lead solder paste will look as follows:

$$F_{m2} = \frac{F_{m2before}}{F_{m2after}} * M_{F_{m2}},$$

where

F_{m2} - parameter representing the overall time for applying the lead solder paste;

$F_{m2before}$ - quantitative parameter before applying the innovation or improvement technologies;

$F_{m2after}$ - quantitative parameter after applying the innovation or improvement technologies;

M_{Fm2} - weighting factor.

Mounting of chip-components

After the positioning of the PCB board has been done, then the mounting of chip-components shall follow up. With the necessity to increase performance of the operation there is a possibility to add an automatic installer. At this stage of PCB assembly process main parameters are performance and amount of automatic installers. In case of one installer, the parameters of the chip-component mounting are as follows (see Table 7):

Input parameters	Processes	Output parameters
Precision of placement of PCB board and template	Positioning of PCB board	Precision of component placement on PCB board
Tackiness of solder paste form (shall create correct geometrical forms)	Capturing of the component	Speed of chip-component mounting
Filling of the template with the solder paste	Mounting of the components	Placing of the component on the board
Speed of the applying of solder paste		

Table 7 – Parameters of mounting of the chip-components

Mathematical interpretation of mounting speed of chip-components can be represented as follows:

$$F_{m3} = \frac{F_{m3before}}{F_{m3after}} * M_{F_{m3}},$$

where

F_{m3} - parameter representing the overall time for chip-component mounting;

$F_{m3before}$ - quantitative parameter before applying the innovation or improvement technologies;

$F_{m3after}$ - quantitative parameter after applying the innovation or improvement technologies;

$M_{F_{m3}}$ - weighting factor.

Mass soldering

Soldering of the mounted PCB board is happening in the convection reflow oven. After chip-components have been placed, PCB boards is being transported on the oven transporter and with defined speed goes into the zones of heating and cooling.

On this stage main parameters of the process are speed of the transporter; the length of the heating zone and the length of the cooling zone of the convection oven (see Table 8).

Input parameters	Processes	Output parameters
Precision of placement of PCB board and template	Equable heating of the item	Endurance of the compound
Speed of placing the chip-components	Smooth controlled growth of the temperature until the needed value	Degree of homogeneity of solder compound
Placing the component	Gradual cooling of the soldered PCB board	Absence of defects

Table 8 – Parameters of soldering for mounted PCB boards

Mathematical interpretation of mounting speed of chip-components can be represented as follows:

$$F_{m4} = \frac{F_{m4before}}{F_{m4after}} * M_{F_{m4}},$$

where

F_{m4} - parameter representing the overall time for soldering;

$F_{m4before}$ - quantitative parameter before applying the innovation or improvement technologies;

$F_{m4after}$ - quantitative parameter after applying the innovation or improvement technologies;

$M_{F_{m4}}$ - weighting factor.

Quality control of the assembly process

After the convection oven PCB boards are taken by the unloader, after which they go to technical control in order to identify whether it meets necessary requirements. After sorting out the boards according to presence or absence of the defects, they are directed to storage or repair areas.

$$F_{m5} = \frac{F_{m5before}}{F_{m5after}} * M_{F_{m5}},$$

where

F_{m5} - parameter representing the overall time for controlling the PCB board;

$F_{m5before}$ - quantitative parameter before applying the innovation or improvement technologies;

$F_{m5after}$ - quantitative parameter after applying the innovation or improvement technologies;

$M_{F_{m5}}$ - weighting factor.

Application of the process approach allows identifying important parameters on each stage of the process and determining the evaluation system for the production manufacturing process in general. Improvement of the assembly process is reached because of optimization of parameters on each of the individual stages of the process.

Minimizing criterion of the lead time of the PCB manufacturing process can be determined as follows:

$$F_m = \sum_{1}^{5} F_{mi} * F_{weight\_i}$$

2.3 Distribution of the weighting factors of the effectiveness criteria

During the process of determination the individual factors for effectiveness of implementing the innovation technologies and improving the overall manufacturing process, the weighting factors have been used, which provide a quantitative value representation of the importance for particular factors.

Minimizing the lead time of the manufacturing process

Distribution of the weighting factors of the effectiveness criteria for minimization of the lead time of the manufacturing process is being done with the help of theory of constraints (TOC) (see Table 9). The biggest value of the weighting factor is being assigned to the constraint activity, the bottleneck process so called, in this case it is assumed as soldering process.

Parameter	**Mathematical expression**	**Weighting factor**
Time for input control	F_{m1}	0.15
Time for applying the lead solder paste	F_{m2}	0.25
Time for chip-component mounting	F_{m3}	0.2
Time for soldering in the oven	F_{m4}	0.3
Time for controlling the PCB board	F_{m5}	0.1

Table 9 – Distribution of the weighting factors for minimizing the lead time of the manufacturing process

Defect factor

As for **defect factor $\mathbf{F_d}$**, which is presented by several parameters such as mechanical defects, defects of material of PCB board and defect of component placement on PCB board, the overall factor for minimizing the defects can be represented as follows:

$$F_d = \sum_{1}^{3} F_{di} * F_{weight\_i}$$

Distribution of the weighting factors for minimizing the defects is being proportional to the amount of defects for each individual factor (see Table 10). The biggest value is given to the parameter which has the higher possibility to have the most defects.

Parameter	Mathematical expression	Weighting factor
Mechanical defects	F_{d1}	0.15
Defects of material of PCB	F_{d2}	0.35
Defect of component placement on PCB (polarity, existence or absence of components)	F_{d3}	0.5

Table 10 – Distribution of weighting factors for minimizing the defects

Product manufacturing quality factor

Factor to identify the quality of the manufactured products is being represented by precision of the component placement on PCB board; by connection strength; by degree of homogeneity of solder joint; by precision of solder paste application and by the degree of filling of the cell stencil of solder paste. It also can be expressed as following:

$$F_q = \sum_{1}^{5} F_{qi} * F_{weight\_i}$$

Distribution of the weighting factors for identifying the quality of manufactured products is being under influence of reliability of the product functioning (see Table 11). The biggest value of weighting factor is given to parameters, which are influencing on reliability of the product functioning.

Parameter	Mathematical expression	Weighting factor
Precision of component placement on PCB	F_{q1}	0.25
Connection strength	F_{q2}	0.25
Degree of homogeneity of solder joint	F_{q3}	0.2
Precision of solder paste application	F_{q4}	0.2
The degree of filling of the cell stencil of solder paste	F_{q5}	0.1

Table 11 – Distribution of weighting factors for quality of product manufacturing

Factor of economic efficiency

In order to identify the economic efficiency, there are several parameters representing it, such as: profit, labour costs, intensity of the usage of the equipment and profitability of production. In general the factor of economic efficiency ca n be shown as:

$$F_e = \sum_1^4 F_{ei} * F_{weight\_i}$$

Distribution of the weighting factors for identifying the economic efficiency is under the influence of the overall performance of the company (see Table 12). The biggest value of weighting factor is given to parameters, which are influencing on the performance of the company.

Parameter	**Mathematical expression**	**Weighting factor**
Profit	F_{e1}	0.3
Labour costs	F_{e2}	0.15
Intensity of the usage of the equipment	F_{e3}	0.15
Profitability of production	F_{e4}	0.4

Table 12 – Distribution of weighting factors for economic efficiency

Factor of staff skill qualification

Staff skill qualification factor can be identifies by three criteria, such as theoretical preparation, practical experience and motivation of personnel as well as can be presented with the following mathematical expression:

$$F_s = \sum_1^3 F_{si} * F_{weight\_i}$$

Distribution of the weighting factors for identifying the staff skill qualification is dependent on the training of the personnel for being able to work on the new equipment (see Table 13). For theoretical preparation of personnel is considered the type of training – distant or on-site as well as for practical experience it is considered the type of preparation – whether it is on real equipment or with the help of virtual technologies. The biggest value of weighting factor is given to parameters, which are dedicated for theoretical and practical preparations on the real equipment (see Table 13).

Parameter	**Mathematical expression**	**Weighting factor**
Theoretical preparation	F_{s1}	0.35
Practical experience	F_{s2}	0.4
Motivation	F_{s3}	0.25

Table 13 – Distribution of weighting factors for staff skill qualification

Factor of automatization

Automatization factor is represented with such parameters as: level of automatization of production, amount of staff involved in production and time to setup equipment for new batch of products. It can be also shown by the following mathematical expression:

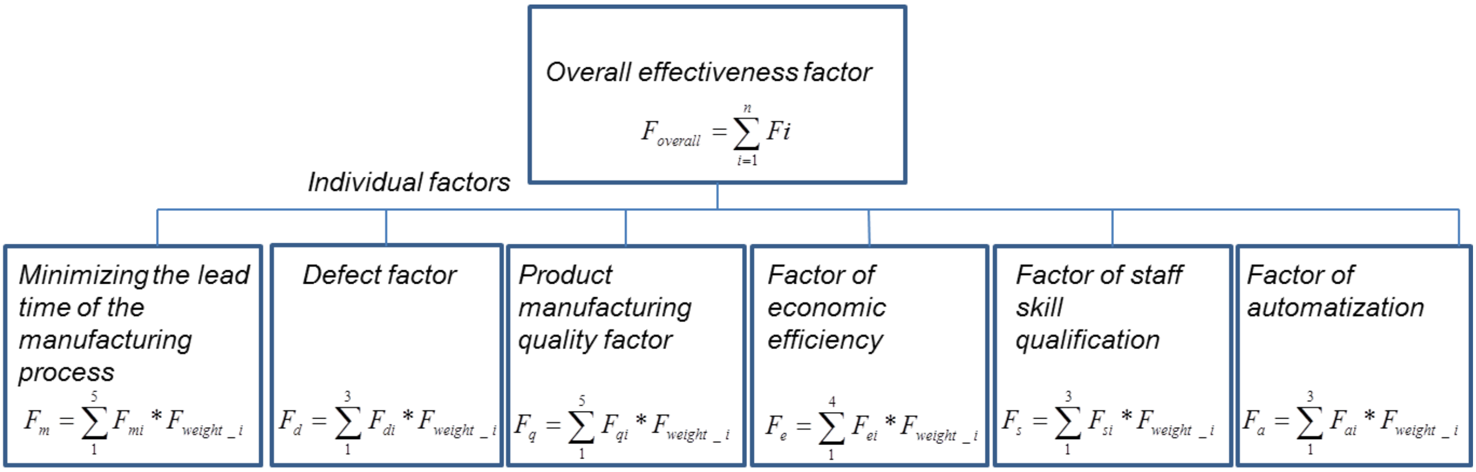
$$F_a = \sum_{1}^{3} F_{ai} * F_{weight\_i}$$

Distribution of the weighting factors for identifying the factors for automatization is interconnected with the reduction of labour mechanization (see Table 14).

Parameter	**Mathematical expression**	**Weighting factor**
Level of automatization of production	F_{a1}	0.4
Amount of staff involved in production	F_{a2}	0.3
Time to setup equipment for new batch of products	F_{a3}	0.3

Table 14 – Distribution of weighting factors for process automatization

The overall structure of mathematical model, which describes the effectiveness of implementing the innovative technologies for the electronics manufacturing process, can be shown as (see Figure 6):



F_{m1}	0.15	F_{d1}	0.15	F_{q1}	0.25	F_{e1}	0.3	F_{s1}	0.35	F_{a1}	0.4
F_{m2}	0.25	F_{d2}	0.35	F_{q2}	0.25	F_{e2}	0.15	F_{s2}	0.4	F_{a2}	0.3
F_{m3}	0.2	F_{d3}	0.5	F_{q3}	0.2	F_{e3}	0.15	F_{s3}	0.25	F_{a3}	0.3
F_{m4}	0.3			F_{q4}	0.2	F_{e4}	0.4				
F_{m5}	0.1			F_{q5}	0.1						

Figure 6 – Overall structure of mathematical model for effectiveness evaluation of implementing innovative technologies into the manufacturing process of PCB assembly

2.4 Conclusion for chapter 2

Based on in depth analysis of PCB assembly process there were several important criteria chosen in order to identify effectiveness of implementing innovative technologies into the manufacturing process. The suggestions from IPC standards were taken into consideration. For quantitative assessment was developed a mathematical model considering individual factors influencing on effectiveness of the manufacturing process, among them are factor for minimizing the lead time of the manufacturing process, defect factor, products manufacturing quality factor, factor of economic efficiency, factor of staff skill qualification and automatization factor.

Mathematical model for evaluation the effectiveness of implementation the innovative technologies into the manufacturing process is based on six individual factors, which are represented by single parameters and weighting factors. Distribution of the weighting factors is being done according to relevance of the single parameters for particularly taken individual factor. Each of individual factors is presented by single parameters, which are determined by the ratio before and after application of innovative technologies and improvement criteria.

3 METHODOLOGY FOR OPTIMIZATION OF PCB ASSEMBLY PROCESS

3.1 Modelling the criteria for quality optimization for PCB manufacturing

Nowadays successful functioning of the manufacturing company is determined by application of effective measures in order to organize the manufacturing process as well as dynamic researches in innovative technologies and new developing directions. Continuous improvement researches also allow the company to formalize the methods and create guidance for management. Usage of the mathematical modelling in order to increase also the quality of output products allows decreasing the time and resources as well as allows having the opportunity to control the manufacturing process and optimize its processes.

Despite the constant growth in the area of electronics manufacturing the focus is aimed mostly on renewal of the existing equipment rather on analyzing all the aspects of the whole process and finding the weak points in order to not only increase the quality of the manufactured products, but also develop a strategy how to effectively manage the manufacturing process and have a model for quantitative assessment.

Electronics manufacturing includes a lot of different processes with different levels of difficultness. One of the most important parts of electronics is PCB assembly process. For the whole assembly process can be applied process approach, which divides the process into several operations. Hence, PCB assembly process can be split into following operations (P1 – P5):

- Input control of PCB blanks (P_1);
- Application of the lead solder paste (P_2);
- Mounting of chip-components (P_3);
- Mass soldering (P_4);
- Quality control of the assembly process (P_5).

Thus the overall process is possible to represent as following:

$$P=\{P_1, P_2, P_3, P_4, P_5\}$$

One of the most important criteria to evaluate the effectiveness of manufacturing processes within the company is **lead time**, which is dependent on complexity of the output product and on effectiveness of applied technologies and methods of organization of production system.

Reduction of the lead time of the manufacturing process is one of the actual interests for each of the current manufacturing companies. Application of the process approach allows reducing execution time of any manufacturing process by optimizing its main operations, which leads as well to reduction of the lead time.

For further descriptions of the processes, there are following variables have been used:

- T – duration lead time of the whole manufacturing process;
- t_i – duration lead time of operation i;

However, it is important to assume, that there is proportionally equal load in all the operations. Proportional load in all the operations is reflected in theory of constraints (TOC). The Theory of Constraints is a methodology for identifying the most important limiting factor (i.e. constraint) that stands in the way of achieving a goal and then systematically improving that constraint until it is no longer the limiting factor. In manufacturing, the constraint is often referred to as a bottleneck. The Theory of Constraints takes a scientific approach to improvement. It hypothesizes that every complex system, including manufacturing processes, consists of multiple linked activities, one of which acts as a constraint upon the entire system (i.e. the constraint activity is the “weakest link in the chain”).

Identification of constraints for reduction of the lead time of the manufacturing process is realized by the maximum time, spent for executing the individual operation ($t_{i\ max}$). According to the theory of Goldratt [25], the bottleneck will be the operation, which has the maximum execution time ($P_i(t_{i\ max})$).

Reduction of the lead time is the main objective for optimization of the manufacturing process:

$$F(t_{i\max}) \rightarrow \min\{Ti\}$$

One of the most effective instruments for increasing the competitiveness of the company along with the constraints theory is the optimization of the manufacturing processes considering the innovative technologies. This will allow in a fast and high quality manner increase the effectiveness of the manufacturing processes based on improvement of manufacturing technologies.

After analyzing the weakest point in the chain and making it stronger, there is a necessity of reanalysing the whole process again and finding new constraint factors, thus, there is a continuous improvement cycle being applied to the manufacturing process.

Within the theory of constraints where limiting operation influences on the lead time of the whole cycle, the most reasonable is to use the method of **Drum Buffer Rope** (DBR), which is able to effectively manage detected constraints. Drum-buffer-rope is a manufacturing execution methodology based on the fact the output of a system can only be the same as the output at the constraint of the system. Any attempt to produce more than what the constraint can process just leads to excess inventory piling up [26]. In our case the bottleneck is the “drum”, which symbolizes the constraints in the manufacturing cycle and gives the rhythm for all manufacturing processes. When the most productive processes are falling into line with the pace rhythm of the slowest process ($P_i(t_{i\ max})$), then the whole manufacturing process is being stabilized and aligned.

The buffer protects the drum, so that it always has work flowing to it. Buffers in DBR provide the additional lead time beyond the required set up and process times, for materials in the product flow. Since these buffers have time as their unit of measure, rather than quantity of material, this makes the priority system operate strictly based on the time an order is expected to be at the drum.

The rope symbolizes the connection between the most productive operation and the drum. The length of the rope is determined by the buffer and limits the resources flowing in the manufacturing process.

In order to identify the constraint it is necessary to carry out the analysis of the PCB assembly process, which consists of five consequent operations:

1. On the first stage, where **input control of PCB blanks (P_1)** is being performed, there are buffers for continuous operation of the automatic line which have been created. Input control is important in order to identify the defects as well as suitability of PCB blanks for the automatic line. Automatic process of the PCB assembly is being performed by executing in parallel the rest of the operations $P_{2\ –}$ P_5.
2. Then PCB blanks are placed into automatic line, **where plating of the lead solder paste (P_2)** is being done with help of jet printer. At this stage the lead solder is

being placed onto the pads through the special stencil which has holes, which represent the exact placement of the pads on the PCB board.

3. **Mounting of chip-components (P_3)** is being done by automatic installer. Its main objective is to correctly place chip-components on the PCB board. Before the mounting a special system is calculating correct placement of the components and then starts the mounting.

   As this operation has the biggest amount of components with different type to be placed, hence it has the biggest lead time value (**$P_3(t_{3\ max})$**). This is a consequence of the fact, that there is a constant growth in requirements for electronic equipment as well as growth in complexity of products, thus growth in the amount of installed components.

4. **Mass soldering (P_4)** process is when after mounting of the chip components PCB board is placed into the reflow oven, where the whole product is evenly warmed up and then cooled down.

5. At the last stage PCB board is taken by the unloader and there is a process of **quality control (P_5)** being performed, where the board is being checked within the recommended requirements of IPC-A-610C standard.

Elimination of the constraint in the operation of the mounting of chip components will allow to reduce the lead time by optimizing main parameters of this operation, such as performance according to IPC 9850 (Surface Mount Placement Equipment Characterization) standard and amount of automatic installers.

3.2 Application of Lean Six Sigma tools to optimize individual process

Once the constraint has been identified it is possible to deepen in analysis using the concepts which are oriented on productivity improvement – Six sigma and Lean production. However, Six Sigma is focused on reducing the variation, defects and improves quality of processes, products and services, when Lean production tries to eliminate waste and reduce cycle times in processes. Together these two methods improve the quality of processes by combining their different approaches. These methods will help to analyse the further actions in order to eliminate the constraint and improve the overall lead time of the manufacturing process, output product and thus improve the quality of the process.

Lean is focused primarily on the flow and speed of processes, as well as waste reduction. Six Sigma is dealing with variation in processes' performance. Lean tools are more intuitive and easier to apply, therefore organizations are recommended to start with lean principles and evolve toward more sophisticated Six Sigma techniques. Lean Six Sigma is a very powerful tool in the domain of strategic management. It combines efficient methods which have separate goals and use the advantages of both of them.

Lean Six Sigma is also a structured methodology that uses a set of management and statistical methods to optimize business processes. In order to map the Lean principles to the Six Sigma methodology, i.e. DMAIC process in particular, it is essential to understand how each phase of DMAIC was used to execute a full scale Lean design effort (see Table 15):

Phase	Tool	Deliverables
Define	Product Family Matrix	Project scope
		Define the value
		Define value boundaries
	FMEA	Identify risks and gaps
	Value Stream Mapping	Define Valuestream
Measure	Value Stream Mapping	Identify major sources of waste
		Layout the VSM timeline
Analyze	VSM analysis	Determine total cycle time
		Identify flow interruptions
		Identify bottlenecks
	Gap analysis	Generate future state VSM
Improve	Solution matrix	Consolidate improvements
	FMEA	Prioritize improvements
	Action Plan	Implementation plan for future improvements
	Metrics dashboard	Improvements summary (before, current, target)
	5S	Visual workplace applications
	Work Standardization	
Control	Control charts	Finalize 5S Sustainability
	Mistake proofing	Finalize Visual Workplace
	Control plan	

Table 15 – DMAIC process and its deliverables in terms of lean six sigma scope

Following each of the phases and its deliverables for chosen tools thus it is possible to analyze and optimize the individual constraint in the process and overall process itself.

PCB assembly process is a complex sequence of many operations, therefore it is important to follow many instructions to get a non-defective workflow or bring the system to a level of minimum losses. Lean and Six Sigma analysis in the mounting of chip components phase will allow identifying the weak points of this phase and finding possible ways for improvement of performance and overall manufacturing process lead time.

DMAIC in PCB assembly process

Define and Measure phases

The first step is to define the objectives and to stay focused on these specifics goals. It is important to identify “critical to quality” (CTQ) metrics which will be the focus. For the measurement it is important to identify how the current process is performing and how many defects are in place.

For the identified constraint (mounting of chip components) it is possible to determine the operations which have higher risks of failing or giving the latency to lead time and measure which are the ones to have influenced on that the most in chosen period of time.

Using FMEA and Value Stream Mapping techniques it is possible to identify the risks and gaps and define the value stream for the mounting process. With the help of value stream mapping to identify daily testing volumes, lead time, cycle time, rework. Important is to create the following objectives:

a. To identify and eliminate time traps

b. To identify and reduce non value added steps

c. To collocate value added steps

d. Reduce complexity and increase flexibility

e. Create a working environment or such a workflow that supports timely flow of all the individual sub operations to be performed.

At the end of the Define phase data shall be collected as well as CTQ points and the understanding of the functioning of the process, possible weak points and how to proceed with it. After the Measure phase, data is being collected and analyzed. After this point it is possible to see some of the key factors that may be affecting process performance.

Analyze and Improve

The next step is to define the drive of the current performance and what is the root cause of the possible delays. For the improving phase the solutions which are positively affecting the performance to be analysed.

The goal of Analyze phase is to identify potential root causes for the process problem being addressed and then confirm actual root cause with data. Having completed the Measure phase, the possible problem has been identified and the circumstances under which it may occur. Once a list of potential root causes has been compiled, the next step is to organize them in a way that makes it easier to prioritize and assess them. Several tools can be used to accomplish this – **fishbone diagram or Ishikawa diagram**, which uses a display resembling the bones of a fish to categorize potential causes and illustrate the levels of causation. The main bones are used to reflect high-level categories, such as People, Processes, Technology, and Policies. Another option is a **tree diagram** which can be used to organize the same information. It is preferable if the amount of information is large and hard to organize in a fishbone. Once the root cause is known, action can be taken in the Improve phase to counter it.

For chip component mounting onto the PCB board to check the accuracy of instruments, confirm key performance variables and acceptable operating range and review operating procedures. Characterize specifications for mounting procedure and try to analyze if the system uses custom experiments.

The goal of Measure phase is to determine the appropriate solutions to implement using objective means, rather than making a decision based on assumptions or preferences. This is a common theme throughout the Six Sigma methodology.

For improving the existing mounting process – add and replace or calibrate the instrumentation, possible add or remove the automatic installers. The statistical analysis will identify key variables that count for the majority of process variation. With usage of such tools as metrics dashboard and 5S it is important to prepare an improvements summary and to visualize the overall mounting process in order to improve bottlenecks which might cause the slowdown of the overall process or eliminate non value added items from it. In order to easier maintain the possible proposed solutions and automate some of the requirements it is recommended to standardize the new solutions and provide with new standard work instructions. By the end of the Improve phase, the solutions are implemented and in fact counter the identified root causes and thus result in substantial improvement in the CTQ metrics.

Control

For the control plan is important to ensure the improvement. For mounting the components it is possible to update the operating instructions, monitor key performance variables and develop procedures for more accurate approach. Calculate possible operating cost savings.

Six Sigma can be applied at different levels, depending on the desired outcome. A single individual can be made responsible for improving one "critical to quality" (CTQ) characteristic of a process. Six Sigma’s main metric is defects per million. However in electrical engineering mostly the focus is to minimize the downtime, workarounds and achieve the optimum lead times.

One of the Six Sigma tools is **control chart** – a graphical representation which provides value in process research by identifying when process changes occur at specific points in time. For one of the sub operations of chip component mounting an analysis of the solder height may be examined. Solder paste has been placed onto the board on the previous operation of plating of solder, it is important to examine the state of the solder in order the chip components would tack to the board and be placed correctly.

It is a very critical factor for PCB manufacturing how well the components will sit on the board and how well they will operate as a result. If the boards are stored or stacked, the solder height determines whether copper in the components will migrate, causing the boards to become defective. To keep solder height within control limits is critical in PCB manufacturing.

Control charts such as X-Bar and Range charting are able to show either the process is in or out of control (see Figure 7 and Figure 8). These charts show that the process is out of control on the X-Bar and in control on the Range chart. This fact indicates that the process average is being influenced by something external from the process. The problem might be with the raw material, with the machine applying the solder or measuring device itself.

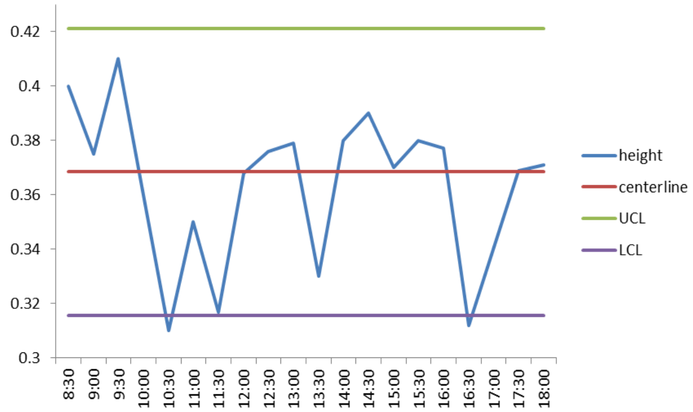


Figure 7 - X-Bar chart

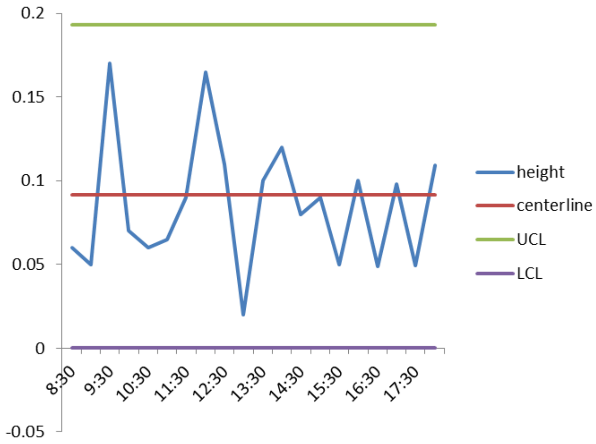


Figure 8 - Range chart

As an **error-proofing (Poka-Yoke) method** for electronics assembly mounting components on PCB may be examined. It is important to consider defects of polarity of the components. If the defects of polarity are being found, then the possible solution is to make parts asymmetrical with a key improvement to modify the part for the right positioning.

Thus using the mentioned above method is possible to put in place a control plan and create control parameters, which will minimize variability and try to eliminate disparity with minimal costs. A plan to monitor the new process shall be established. The monitoring plan clarifies how the process performance will be continuously monitored, who will be notified if there is a problem and how that will happen and what response is required. The monitoring plan also indicates what constitutes satisfactory performance and what should be considered a red flag indicating possible problems.

By following the Six Sigma DMAIC methodology, process improvement can be accomplished in a way that is systematic, sustainable, confirmed with data, and in alignment with customer and stakeholder quality expectations.

3.3 Application of fuzzy logics on Lean Six Sigma technics to optimize the lead time

One of the possible improvement measures for the chip component mounting sub process is application of fuzzy theory and focusing on the way for optimization the lead time and seeking for increasing the quality of output product.

The DMADV flow is the same as DMAIC algorithm described in previous section that can be applied to design or redesign of products or processes (Design for Six Sigma or DFSS). It will help to redesign the process for chip component mounting in the most optimal way. The process of activities of DFSS consists of four stages: Identify, Design, Optimise and Validate (IDOV).

Stage 1: Identify

This stage is driven by the Critical to Quality (CTQs) factors that have to be considered during the product or process design.

Stage 2: Design

The main purpose of this stage is to analyse and evaluate the design requirements, key design parameters and their relationship with CTQs. Setting up output variables and develop a transfer function using fuzzy principles.

Stage 3: Optimise

It is to develop the detailed design of products or processes that would meet CTQs and also to optimise the developed design. On this stage fuzzy logic is being applied, membership function is being developed with its rules.

Stage 4: Validate

It is to verify the proposed design to ensure that it meets the identified CTQs and goal.

A. Identify

The quality function deployment (QFD) method should be employed to identify the most significant indicators with the aim of finding the weak points which effect the lead time of individual operations as well as overall lead time of the manufacturing process.

B. Design

This stage is concerned with identifying key input and output variables for the proposed model. The brief review of Lean Six Sigma in previous chapters indicated that the current key performance indicators for lean six sigma focus on the improvement of quality, cost, time and service.

A theoretical function in order to analyze quality of production after particular operation incorporates fuzzy set theory and provides a way of monitoring and optimizing of the whole manufacturing system. *Optimization* in this context means minimizing lead time values for individual operations and thus minimizing the overall lead time of the manufacturing process. Essentially vague and subjective information often found in the fuzzy manufacturing environment of variability, complexity and constraints make it a difficult environment to control and improve. Therefore modelling with fuzzy set theory is a useful performance monitoring tool to incorporate. Fuzzy control operates on a continuous value basis (between 0 and 1) by means of converting a linguistic control strategy, based on human expert knowledge, into an automatic control strategy. Fuzzy logic is used by the controller to apply reasoning to an error and attempts to rectify it through a rule based algorithm.

C. Optimize

A transfer function is a mathematical representation of the relationship between the input and output of a system or a process. It facilitates the optimization of process output by defining the true relationship between input variables and the output. *Optimization* in this context means minimizing the requirement variability and shifting its mean to some desired target value. The transfer function can be presented as indicator of quality of production after the specific operation and refined with the use of fuzzy logic:

$$\textit{Quality of production} = F\ \{\textit{positioning, capturing, mounting}\} \tag{1}$$

Usually transfer functions resulting DMADV implementation are expected to have a mathematical representation. However, in this thesis the transfer function is presented as sets of fuzzy logic rules evaluated using the Xfuzzy software - the fuzzy system development environment which integrates a set of tools that ease the user to cover the several stages involved in the design process of fuzzy logic-based inference systems, from their initial description to their final implementation [61].

Fuzzy inference is the process of formulating the mapping from a given input to an output using fuzzy logic (major stages being fuzzification, rule evaluation and aggregation, and defuzzification). The mapping of defuzzified results onto the problem situation then provides a basis from which decisions can be made.

Essentially vague and subjective information often found in manufacturing environments of variability, complexity and constraints make it difficult environment to control and improve. Therefore modelling with fuzzy set theory is a useful performance monitoring tool to incorporate.

The steps for assessing the quality of production using the fuzzy inference system are fuzzification, rule evaluation and defuzzification. There are two types of fuzzy inference systems that can be implemented: Mamdani-type and Sugeno-type. The two types differ in the way output is determined. In the Mamdani-type, after the aggregation process the output membership function of the output variable is a fuzzy set (see Figure 14), while a Sugeno-type uses a constant value as the output membership function. After the aggregation process, there is a fuzzy set for each output variable that needs defuzzification. The first two parts of the fuzzy inference process, fuzzifying the inputs and rule evaluation and aggregation are exactly the same. The main difference between Mamdani and Sugeno is that the Sugeno output membership functions are either linear or constant. Since quality of production cannot be judged in terms of discrete values, a Mamdani-type inference system is selected for evaluating and aggregating the fuzzy rules in this case.

Fuzzification

The fuzzification process is performed during run time and consists of assigning membership degrees between 0 and 1 to the crisp inputs of positioning, capturing and mounting.

Rule evaluation

The rule evaluation process consists of using the fuzzy value obtained during fuzzification and evaluating them via the rule base in order to obtain a fuzzy value for the output. The rule evaluation follows the form of **IF** (condition x) and (condition y) **THEN** (result z) rules are applied. Basically the use of linguistic variables and fuzzy IF-THEN- rules utilize the imprecision tolerance and uncertainty as well as simulating the ability of the human mind to summarize data and focus on decision-relevant information. These rules are based on expert knowledge and experience.

Defuzzification

The fuzzy inference system using Mamdani's fuzzy implication rule determines the appropriate fuzzy membership value. The defuzzification process consists of combining the fuzzy values obtained from the rule evaluation step and calculating the reciprocal in order to get one and only one crisp value that the output should be equal to. The output 'quality of production' is evaluated in relation to the crisp value and translated into linguistic terms (see Table 19).

Fuzzification of quality of production transfer function

Figures 9 and 10 depict the empirical transfer function from equation (1) as a fuzzy logic system with inputs and output being fuzzified using appropriate membership functions. The following sections narrate each component of the system.

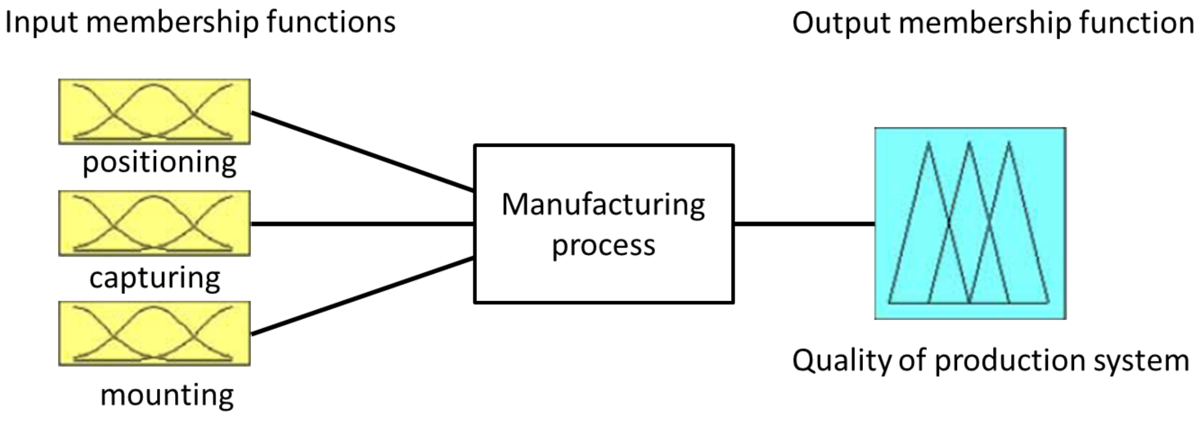


Figure 9 – Transfer function of quality of production system

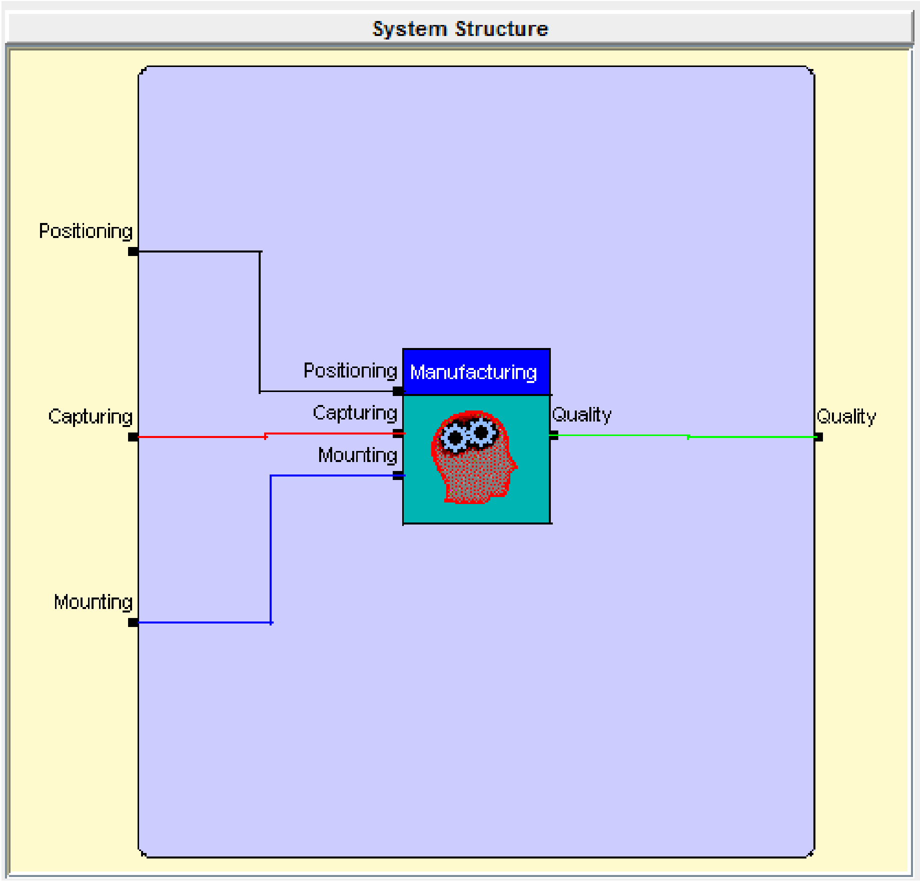


Figure 10 – Transfer function of quality of production system defined in Xfuzzy

Positioning

Precision of placement of PCB board and stencil is measured. The categories in the measure are described in Table 16. The categories are just an indication to know what would be the optimal precision to be chosen in order to decrease the lead time for chip placement operation and thus to decrease the overall lead time for PCB assembly process.

Fuzzy	**Linguistic term**	**Range (µm, can vary for different equipment for chosen sigma)**
1	Low	More than 60
2	Acceptable low	50-60
3	Regular	45-50
4	High	35-45
5	Very high	More than 25

Table 16 – Positioning measurement

'Regular' term indicates the chosen optimum value for the existing equipment, however by changing the precision in combination with the other parameters it can lead to saving in lead time. Any precision which is lower than 60µm is considered to be unacceptable.

Furthermore, Figure 11 shows the fuzzy sets "Positioning" that represents the standard in degree of membership. For the Low standard, the degree of membership is 0, while the Regular standard has a degree of membership of 1. The rest of the standards are represented within the range 0 to 1 degree of membership with the boundaries between the standards graded. This provides the fuzzy set sensitivity to the membership function by providing degrees of closeness to the required value of the quality of production.

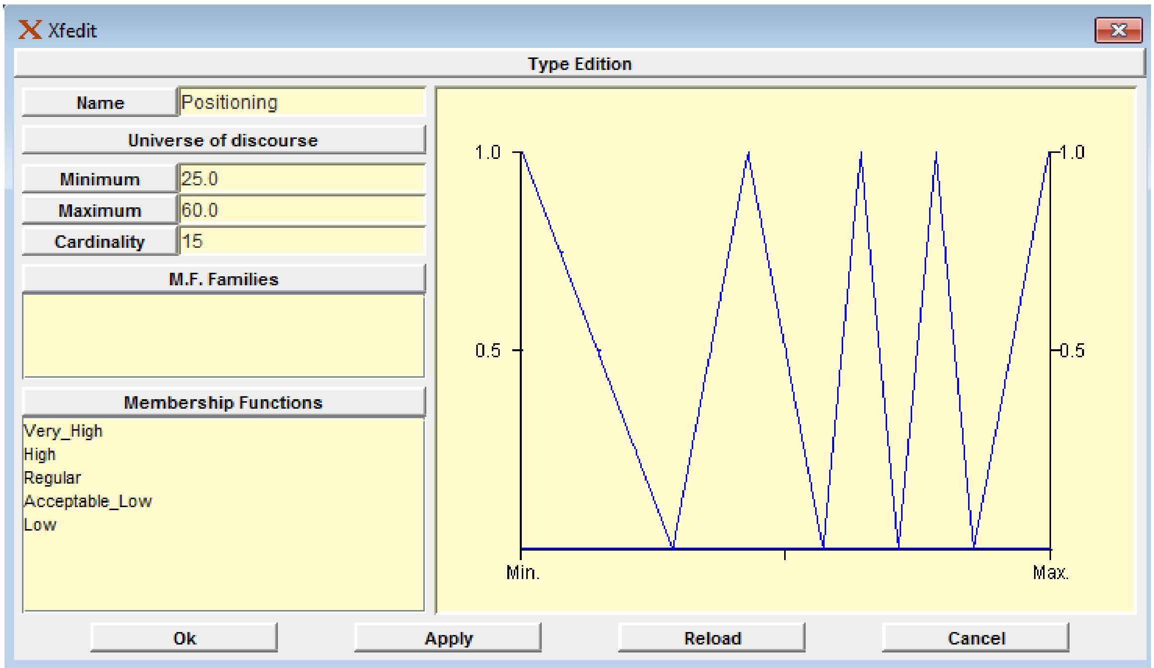


Figure 11 – Input variable "Positioning"

Capturing

The tackiness of solder paste is considered for the further capturing of the components and placing then onto the PCB board. Tackiness expresses the ability of the solder paste to grab the component and keep it in place and can be classified into two terms, tack time and tack force. Tack time is the length of time that a solder paste can stay tacky enough to hold a component in position after printing. Tack force indicates the strength of adhesion that the solder paste exhibits in order to hold a component. This is important when the pick and placement machine has a table which moves in two directions towards the placement nozzles.

It is also an important feature for odd shape, high and or heavy components. Tackiness can vary over time. Theoretically, the solder paste‘s sidewalls are perfectly straight after the paste is deposited on the circuit board, and it will remain like that until the part placement. If the paste has a high slump value, it might deviate from the expected behaviour, as now the paste‘s sidewalls are not perfectly straight. A paste‘s slump should be minimized, as slump creates the risk of forming solder bridges between two adjacent lands, creating a short circuit.

There are three categories to consider if the tackiness of solder paste achieved the required level: "low", "medium" and "high" as shown in Table 17. However, the categories are just an indication to identify whether chosen solvent influences on the speed of placement of chip components and to identify the best solvent which might decrease the lead time for the chip component mounting operation by having the higher tack strength in the placed solder paste. Any capturing tackiness which is below 100gf shall be unacceptable. "Medium", while acceptable, shows that the capturing standard needs to be improved aiming towards achieving "High". For the "Low" standard, the degree of membership is zero, while the "High" standard has a degree of membership of one. The rest of the standard is presented within the range 0 to 1 degree of membership. The boundaries between the standards are graded which provides the fuzzy set sensitivity to the membership function by providing degrees of closeness to the required value of the quality of production system (see Figure 12).

A test can be done in a way that a test probe is pressed onto each deposit for some seconds with some load and it is then pulled back and the tensile strength is measured. The goal is to determine how long the paste stays sticky enough (the assumption is the minimum adhesion required to hold a component as more than 100gf.).

Fuzzy	**Linguistic term**	**Range (gf, can vary for chosen solvent)**
1	Low	Below 100
2	Medium	100 - 160
3	High	Above 160

Table 17 – Capturing measurement

What largely contributes to the tack time characteristics, are solvents. Tackiness itself is correlated with stencil life and slump resistance, as the evaporation rate of solvent is the main determining factor. It is normally desirable to use a higher boiling point solvent as it evaporates at a slower rate and preserves long tack time. Some concern is required as to what type of solvent is to be used, because it in turn tends to cause slumping of the solder paste when a high boiling point solvent is formulated.

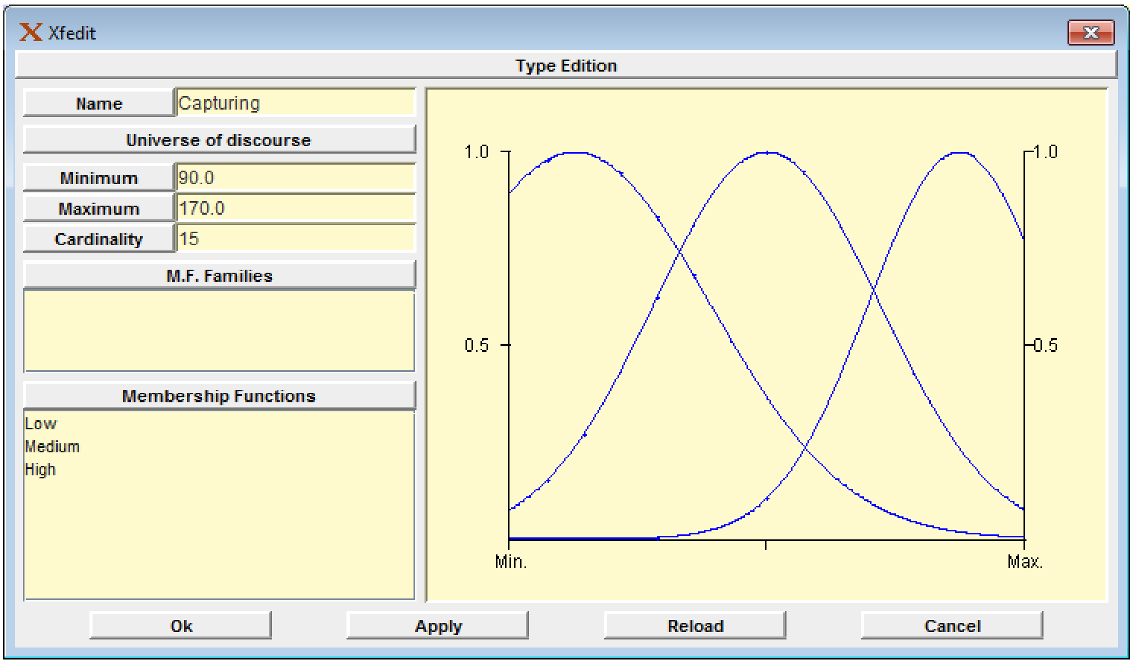


Figure 12 – Input variable "Capturing"

Mounting

Speed of applying the solder paste for further mounting the chip components will determine the last input variable in fuzzification process. The categorization is based on the amount of components placed onto the PCB board and is presented in Table 18.

Fuzzy	Linguistic term	Range (components/hour, can vary for different equipment)
1	Low	Below 15 000
2	Medium	15 000 – 25 000
3	High	Above 25 000

Table 18 – Mounting measurement

There are three categories to consider if the mounting of components achieved the required speed: "low", "medium" and "high". Any speed which is below 15 000 components per hour is considered to be low. High speed is defined as the one which exceeds 25 000 components per hour. For the "Low" standard, the degree of membership is zero, while the

"High" standard has a degree of membership of one. The rest of the standard is presented within the range 0 to 1 degree of membership. The boundaries between the standards are graded which provides the fuzzy set sensitivity to the membership function by providing degrees of closeness to the required value of the quality of production system (see Figure 13).

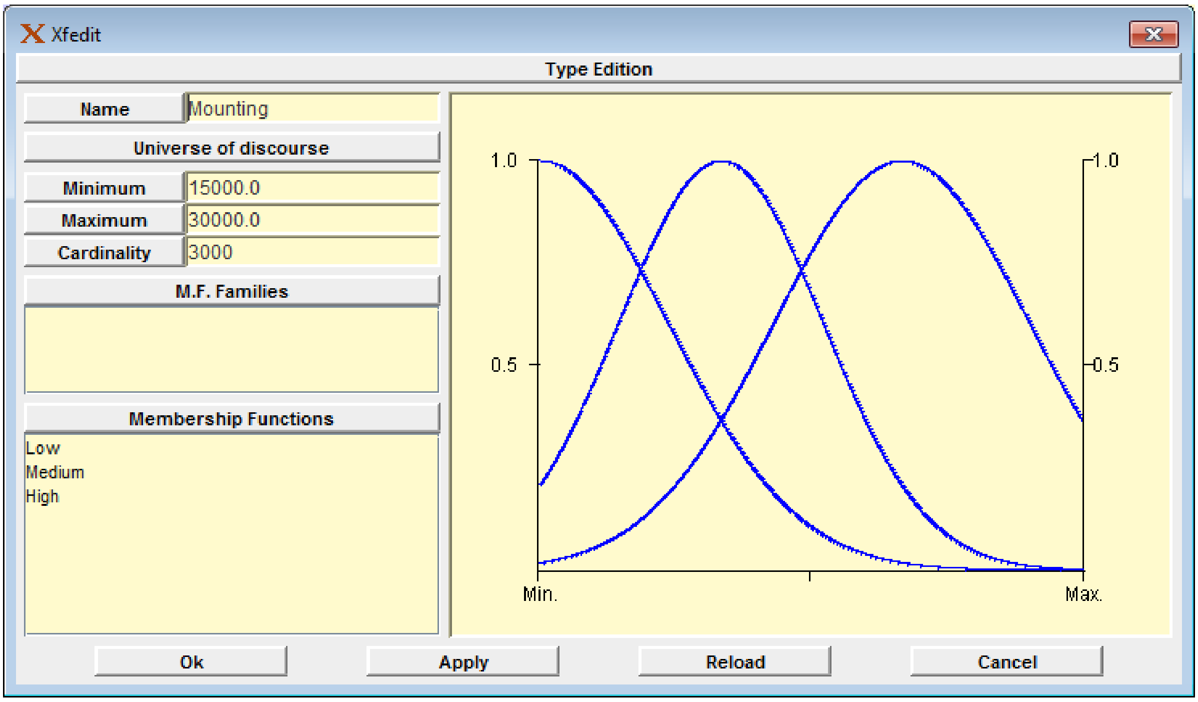


Figure 13 – Input variable "Mounting"

Quality of production system as output

Quality of production system is determined by speed of production, by number of produced items and amount of errors or defects. Any value for quality of production system between the values of 0 and 0.29 will be rejected, between 0.30 and 0.49 indicates that the lead time is poor and needs attention. Although the quality value from 0.50 to 0.69 indicates acceptance it shows a high gap from the optimum and the processes need the attention. Value between 0.70 and 0.89 indicates a level of satisfaction aiming to close the gap towards optimum. The output value between 0.90 and 1 indicates that the lead time is fulfilling the requirements and requires the processes to be monitored and maintained (see Table 19 and Figure 14).

Linguistic term	Scores
Optimum	0.9 – 1
Satisfied	0.7 – 0.89
Acceptable	0.5 – 0.69
Poor	0.3 – 0.49
Reject	0 – 0.29

Table 19 – Ranges for qualifying quality of production

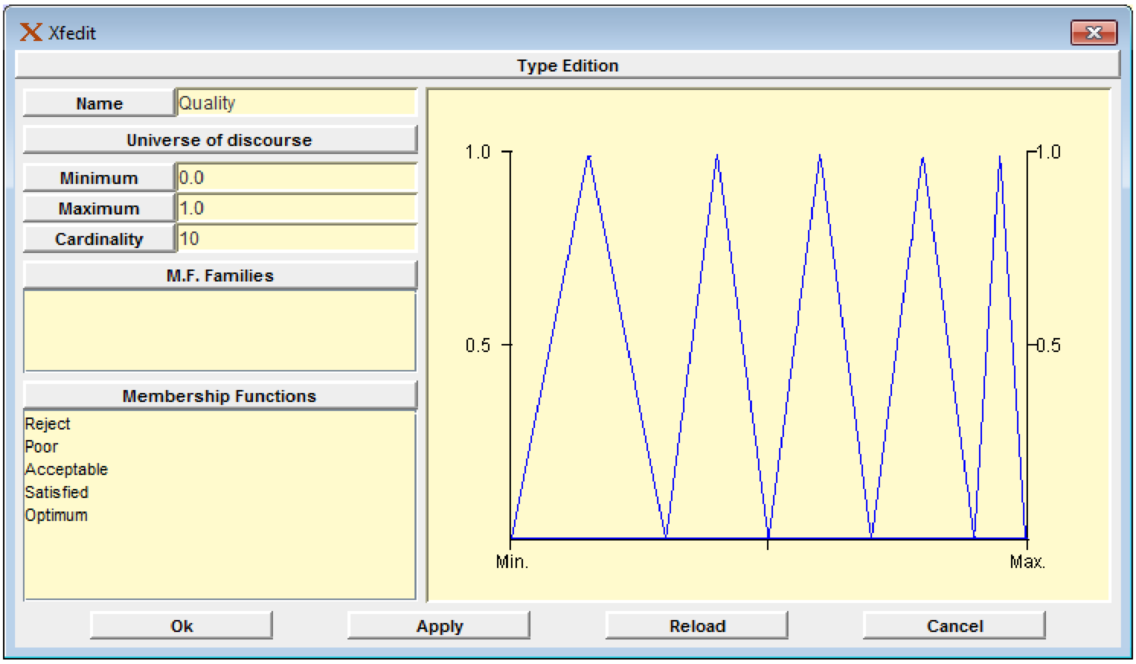


Figure 14 – Output variable “Quality”

Fuzzy evaluation rules

Table 20 demonstrates the rules following the format “if (condition x) and (condition y) then (result z)” corresponding to the combinations of input conditions. For example: if tackiness of solder paste is “medium” and if precision of placement is “regular” and if speed of applying of solder paste is “low” then the quality of production system is “acceptable”. The rules are determined through expert knowledge and they can be refined following real life application which will confirm them or require them to be modified.

Mounting "low" (speed applying of solder paste)			
Capturing / Positioning	**Low**	**Medium**	**High**
Low	Reject	Reject	Reject
Acceptable low	Reject	Poor	Acceptable
Regular	Acceptable	Acceptable	Satisfied
High	Acceptable	Satisfied	Optimum
Very high	Satisfied	Satisfied	Acceptable
Mounting "medium"			
Capturing / Positioning	**Low**	**Medium**	**High**
Low	Reject	Reject	Reject
Acceptable low	Reject	Poor	Acceptable
Regular	Acceptable	Satisfied	Optimum
High	Acceptable	Acceptable	Acceptable
Very high	Poor	Reject	Reject
Mounting "high"			
Capturing / Positioning	**Low**	**Medium**	**High**
Low	Reject	Reject	Reject
Acceptable low	Acceptable	Satisfied	Acceptable
Regular	Poor	Poor	Poor
High	Poor	Poor	Reject
Very high	Reject	Reject	Reject

Table 20 – Fuzzy rules for mounting "low", "medium" and "high"

There were 45 evaluation rules described in the fuzzy system in order to replicate the defined logic (see Figure 15).

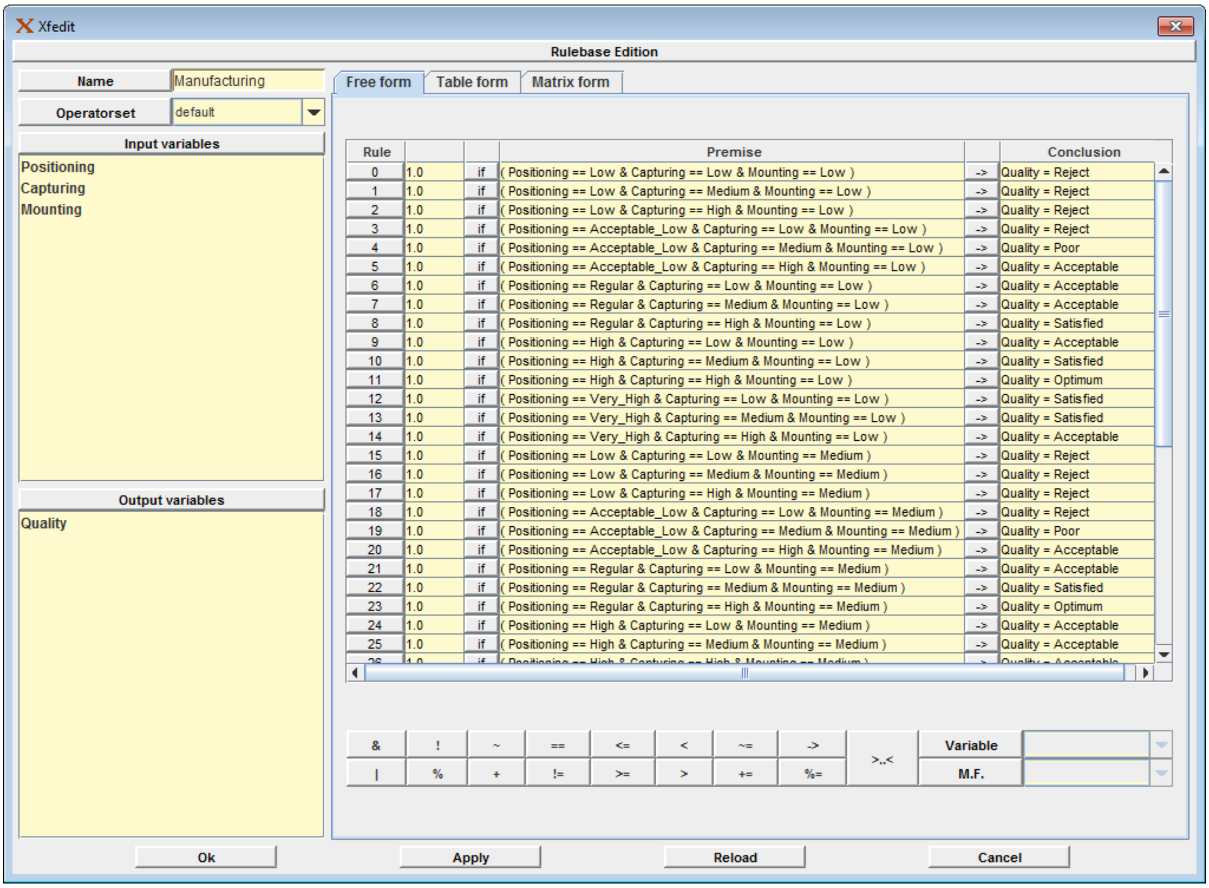


Figure 15 – Fuzzy rules described in Xfuzzy system

Fuzzy solution results

The three inputs can be set within the upper and lower specification limits and the output response is calculated as a score that can be translated into linguistic terms. Using the monitorization feature of Xfuzzy tool is possible to see the fuzzy output solutions for equation (1).

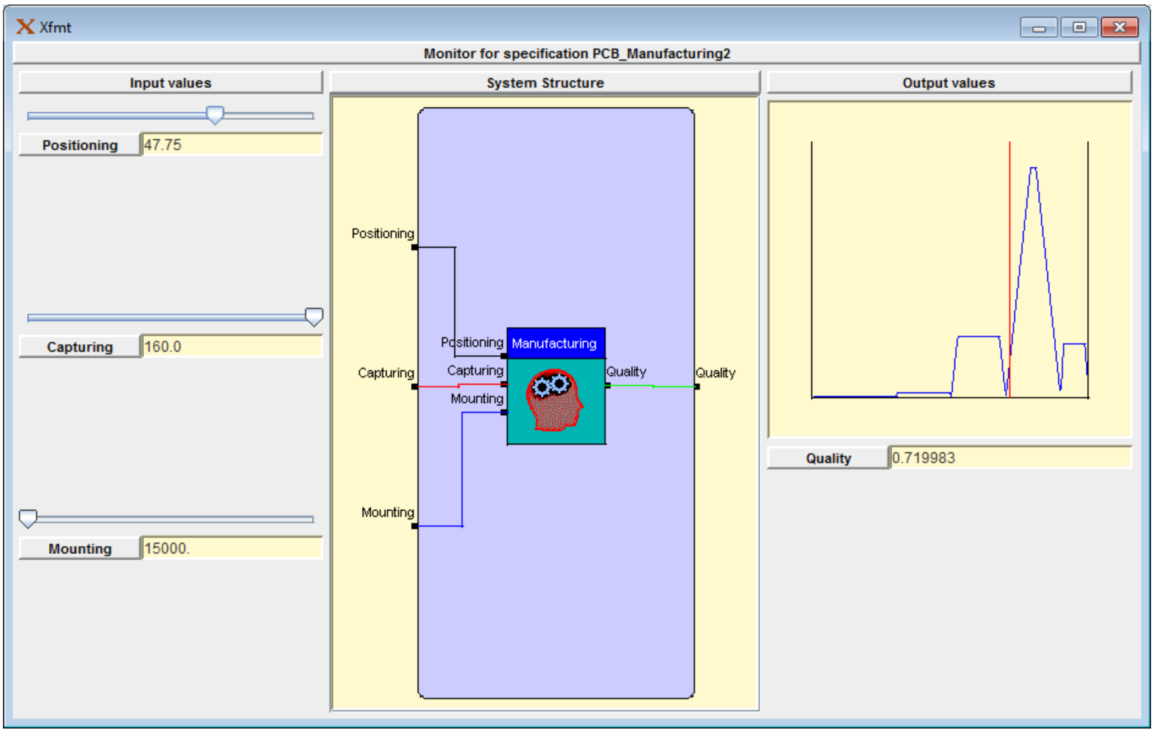


Figure 16 – Membership values for a quality output indicating “satisfied” level

In this instance the quality output of 0.7199 indicates “satisfied” linguistically from Table 19 (see Figure 16). The satisfied result is achieved with combination of regular precision for around 47.75 µm and high tackiness of the solder paste of around 160gf, considering that speed of applying the solder paste is low. If the mounting speed would be growing the output quality with mentioned above combination of positioning and capturing would be dropping. However by increasing the speed of mounting the components to medium level and keeping the capturing level of tackiness within medium range as well, the output result for optimizing the lead time and quality of production system lays within the 0.6 result (see Figure 17), which corresponds to “acceptable” linguistically term from Table 19 and can be considered as one of the possible solutions for tuning the PCB assembly process in order to achieve satisfactory level of optimization of the lead time and increase the quality level of output product.

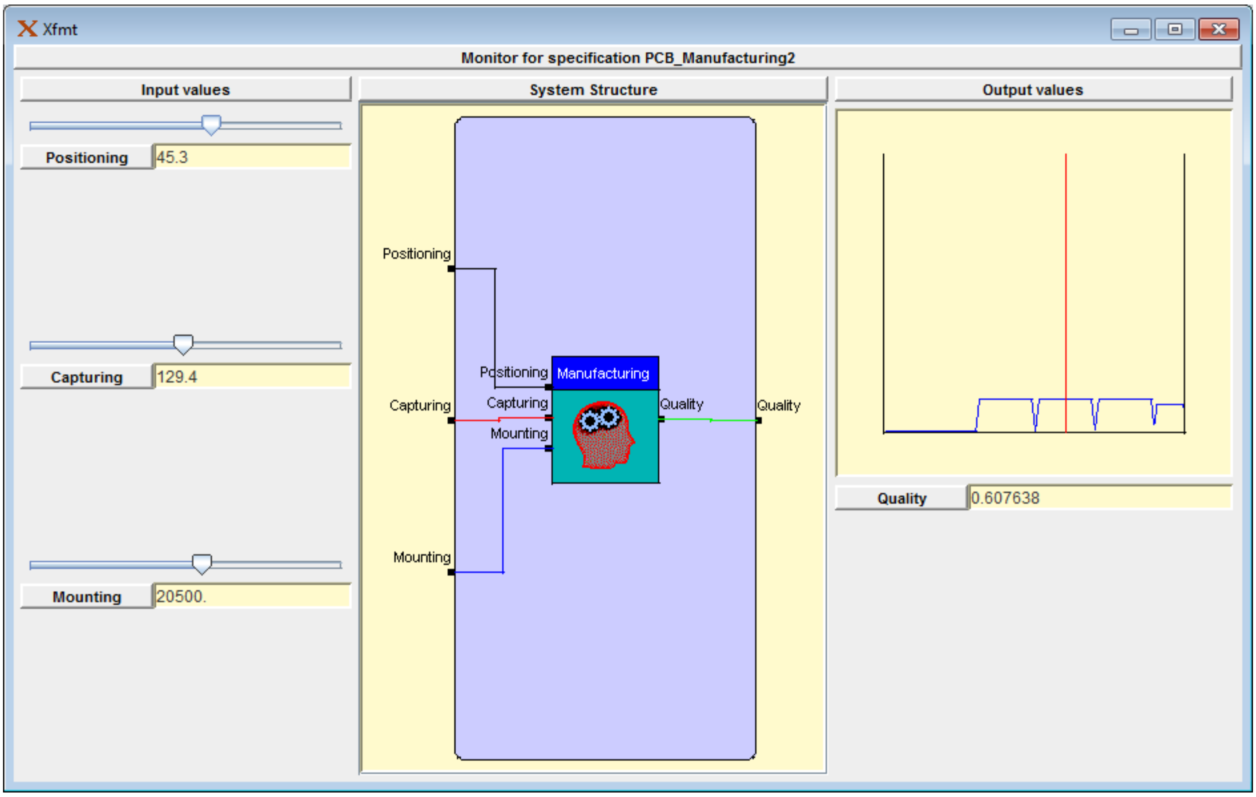


Figure 17 – Membership values for a quality output indicating “acceptable” level

As long as speed of applying solder paste for further mounting of chip components is high, then the quality of output product will be within “satisfied” or “acceptable” range taking into consideration that precision of placement shall be maintained within regular range and tackiness of solder paste within medium strength. Figure 18 depicts the degree activation of the fuzzy rules within the capturing lying in medium range and positioning of components within regular to acceptable low range. Thus, Rule 34 and Rule 35 were activated and trigger the quality output value lying within borders of “satisfied” and “acceptable” values (see Figure 19).

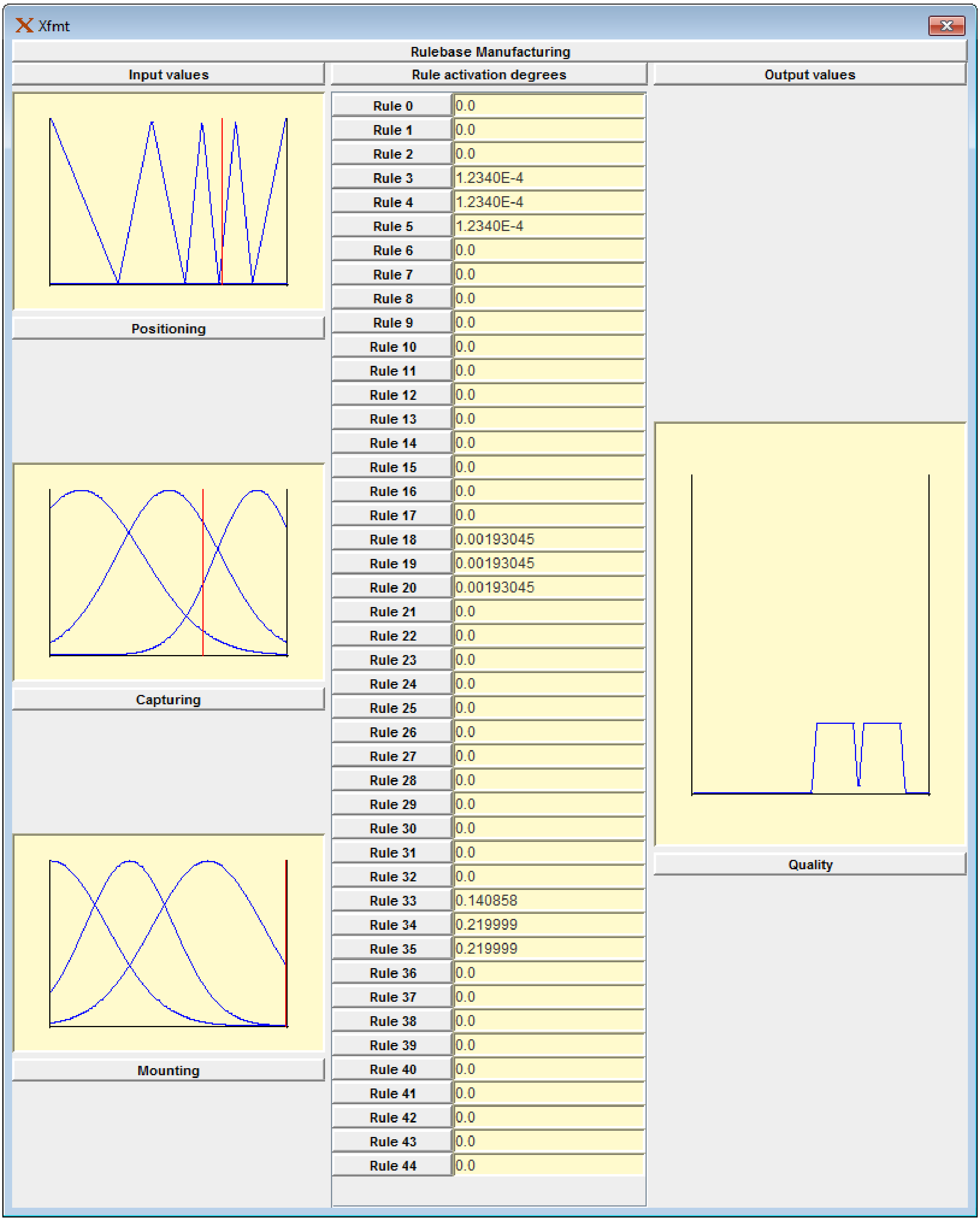


Figure 18 – Rule activation degrees of the fuzzy inference system

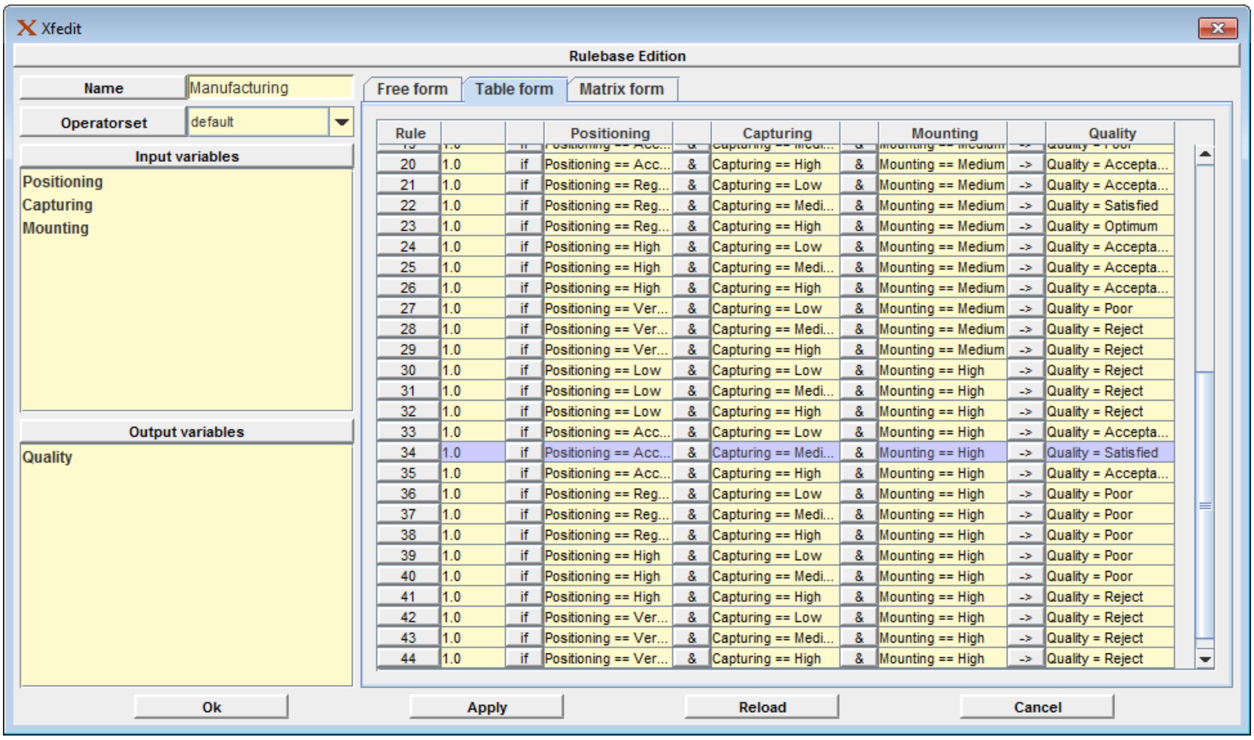


Figure 19 – Rule base viewer of the fuzzy inference system

A further graphical representation as a response surface is presented in Figure 20, 21 and 22. However, two axes of the three input variables can be selected to map the resulting variations in the output of quality. The figures uncover the representation of optimal values in three dimensional plateau. It is seen that there are several peak areas, which represent the possible optimal solutions for output quality of the production system which will eventually lead to optimizing the manufacturing process.

In Figure 20 the quality achieves high values when the positioning is within the middle range, which corresponds to regular precision and capturing is towards higher end. As the positioning is towards higher precision, then it requires more time to place the component on the board, thus there might be less time for capturing phase and this if it goes towards higher end then output quality drops as the processing lead time would be much increased.

Figure 21 depicts the quality behaviour in relation to variations in positioning precision and mounting speed. With higher mounting speed and lower precision the quality achieves higher values.

Figure 22 presents the quality response surface with capturing and mounting as input variables. The relatively smooth surface depicts the quality score to be decreased with higher speed of mounting and higher tackiness capturing.

Such a system with fuzzy logic analysis helps with decision making processes, improving the quality, service design and many others. This example presents the use of fuzzy logic to design an evaluation of the optimal setup of input parameters in order to enhance the quality of manufacturing process as output service.

Fuzzy logic deals with information in the same indefinite terms that characterize human speech and perceptions. By developing membership functions representing speed or precision by evaluating them with human perception, this gives us means of quantifying the rules of thumb that experts use in describing interactions in a complex system.

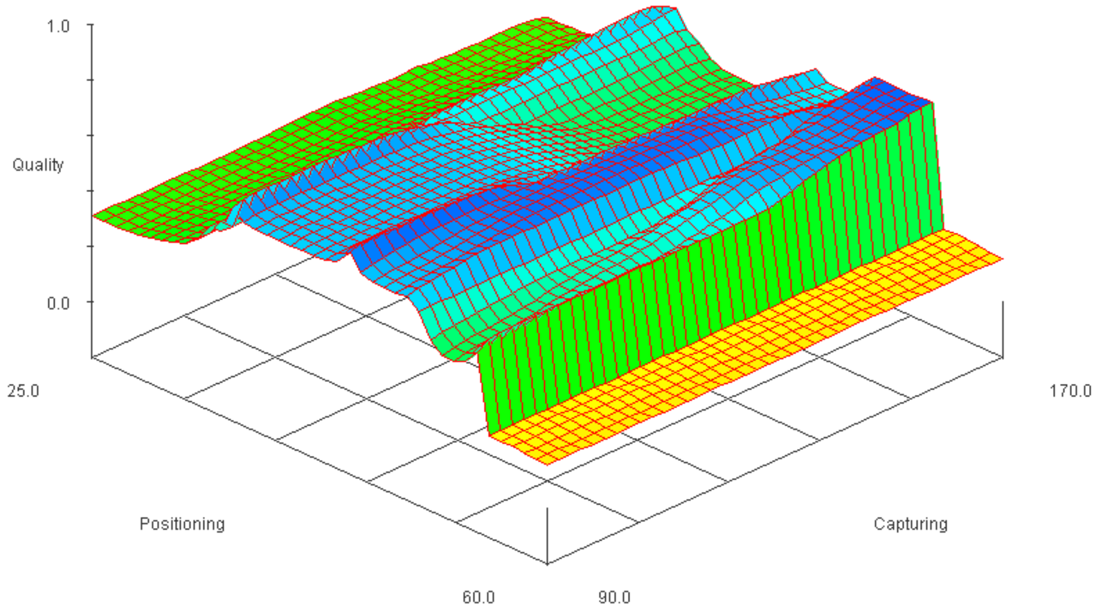


Figure 20 – Output surface of the fuzzy inference system for positioning and capturing

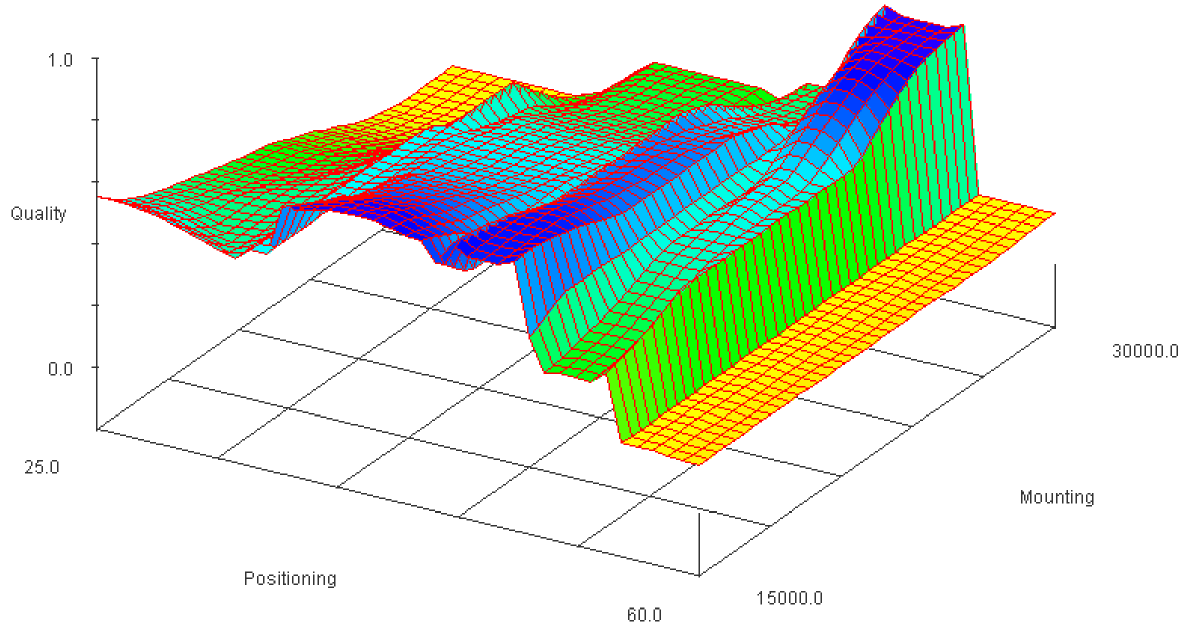


Figure 21 – Output surface of the fuzzy inference system for positioning and mounting

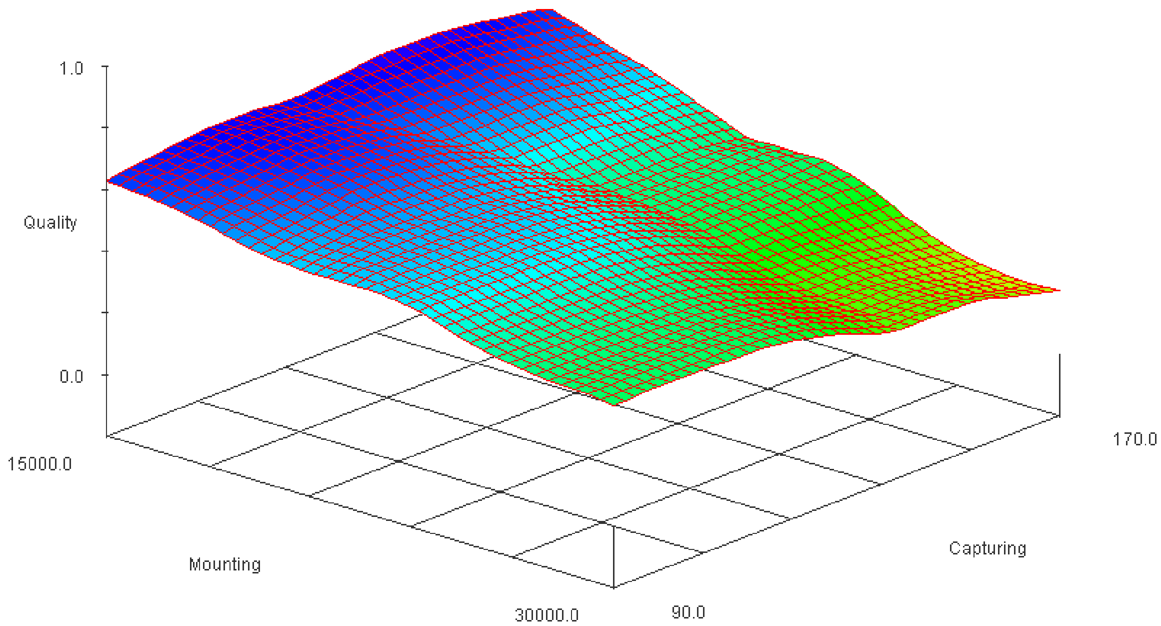


Figure 22 – Output surface of the fuzzy inference system for capturing and mounting

D. Validate

The model is to be analysed and validated to ensure that performance indicators provided would meet the identified requirements. The developed model should be modified and verified continuously to ensure that the model satisfies the requirements. This includes the application of fuzzy evaluation rules. The flow of IDOV activities facilitates the continuous improvement effort. The predictive model or transfer function is a step of key importance to predict the system performance in terms of output variables by varying independent key input variables. Keeping the fuzzy nature of categorizing manufacturing performance level, fuzzy logic was used to develop the transfer function and provide a means of putting quantitative value on qualitative measurement.

The methodology described can be applied to diverse manufacturing processes. It provides the flexibility to tailor make process control and accommodate changing needs as they arise. This also makes DMAIV an adaptable methodology for monitoring and controlling performance in complex and variable manufacturing environments.

3.4 Conclusion for chapter 3

Criteria for optimizing the PCB manufacturing process has been analyzed and identified. The criteria are based on minimizing the lead time of the sub operations (i.e. sub operation of mounting the chip components, which has the biggest processing time because of the largest amount of components to be placed on the board) of manufacturing process which will lead to minimizing the overall lead time.

With the help of theory of constraints the most important limiting factor (i.e. constraint) was identified. Hence, considering the limiting factor lean six sigma and fuzzy logic methodologies were analyzing it further trying eliminating the constraint, finding out the root cause and optimizing the process.

4 PERFORMANCE EVALUATION OF PCB MANUFACTURING PROCESS

4.1 Optimal strategy for implementing innovations into the manufacturing process

Nowadays there are strict requirements for the product quality and these requirements grow on the market every day more and more. This fact brings the necessity of reconsideration of existing equipment of technological line and manufacturing process as well as implementation of innovative technologies.

Innovative technology is considered as technology which brings to more-effective products, processes, services, technologies, or business models that are readily available to markets. Restructuration of the organization and manufacturing is one of the innovation techniques. Usually this process starts from collecting the information about the current market situation and what are the current technologies being used within the competitive organizations. Based on the gathered information company is going to the manufacturing process to create the product. However, it is important to accommodate the process according to the changing fluctuations in technologies, markets and competitive organizations. Getting the advantage on the market is possible only with the well-developed strategic planning based on the innovative technologies.

Having the step by step process approach for designing the method of optimization gives the opportunity on the initial stage to define main parameters for optimization of sub processes and main criteria for effective application of innovative technologies in the PCB manufacturing process.

Optimization of the parameters of the manufacturing process and finding the optimal setup of the equipment in order to minimize the overall lead time is one of the main methods of effective implementation of innovative technologies into the production system.

The model for optimization described in previous chapters has given the overview to decrease the processing time for operation of mounting the chip components onto the PCB boards. However, elimination this bottleneck point of the whole manufacturing process brings to the next stage of optimization, where it is needed to find the next constraint which might cause the delay and consider finding the solution for optimizing there as well.

On the basis of the obtained conclusions the organization can develop the internal standard how to implement innovative technologies into their existing process, respectively reconfigure the existing equipment or change it, calculate the lead times of different sub operations and analyze where possible weak points of the system are.

4.2 Quality management system scheme of process interaction

In order to integrate the innovative technologies into the existing and functioning manufacturing process, important fact to consider is to design a detailed quality management system scheme for interactions between processes.

A quality management system (QMS) is a set of policies, processes and procedures required for planning and execution (production/development/service) in the core business area of an organization. (i.e. areas that can impact the organization's ability to meet customer requirements.) It is as well a complex set of different processes and methods needed for successful managing of quality of output products.

Managing such a complex system is one of the main goals of each of the organization which wants to be competitive on the current market. One of the instruments which allow structuring all the processes is a QMS policy manual, where would be described the main scheme of interaction between processes of the system.

A QMS process is an element of an organizational QMS. The ISO9001:2000 standard requires organizations seeking compliance or certification to define the processes which form the QMS and the sequence and interaction of these processes.

Examples of such processes include:

- Order Processing;
- Production planning;
- Measurement of product, service, process compliant with specified requirements including statistical techniques such as Statistical Process Control and Measurement Systems Analysis;
- Calibration;
- Purchasing and related processes such as supplier selection and monitoring.

ISO9001 requires that the performance of these processes be measured, analysed and continually improved, and the results of this form an input into the management review process.

Design of the QMS scheme of process interactions will allow to significantly increasing effectiveness of management of the organization as well as functioning of the whole quality management system.

CONCLUSION

The thesis achieved the stated objective and set goals have been resolved.

Main results corresponding to the set goals of the thesis are as following:

1. The conducted analysis on current electronics market situation has shown that there is tendency in size decrease of electronic components and increase in requirements for their reliable and efficient functioning. Thus there is a need in developing new technologies for electrical engineering manufacturing processes.

   Optimization of manufacturing processes through the implementation of innovative technologies is one of the effective instruments for increasing the competitiveness of the company as well as increasing the quality of manufactured products. As a contribution of the research new criteria of effectiveness for implementation of innovative technologies into a printed circuit board manufacturing process were proposed. It allows estimating the results for restructuring the current technological line for manufacturing taking into account the individual factors of effectiveness for each sub operation of the process.

2. Analysis of the printed circuit board assembly process and the usage of the proposed effectiveness criteria for implementing innovative technologies allowed designing a mathematical model for effectiveness evaluation. Designed mathematical model considers individual factors influencing on effectiveness of the manufacturing process and leading to improving the overall quality of the process. Among the individual factors analysing the effectiveness of implementing the innovative technologies for the electronics manufacturing process, are:
   a. factor for minimizing the lead time of the manufacturing process;
   b. defect factor;
   c. products manufacturing quality factor;
   d. factor of economic efficiency;
   e. factor of staff skill qualification;
   f. automatization factor.

As a contribution of the research a new mathematical model for evaluation of implementing innovative technologies into the manufacturing process of printed circuit board assembly has been developed, consisting of distribution of weighting factors for each individual operation influencing on efficient functioning of manufacturing process.

3. Criteria for optimizing the printed circuit board manufacturing process has been analyzed and identified. The criteria are based on minimizing the lead time of the sub operations (i.e. sub operation of mounting the chip components, which has the biggest processing time because of the largest amount of components to be placed on the board) of manufacturing process which will lead to minimizing the overall lead time. With the help of theory of constraints the most important limiting factor (i.e. constraint) was identified. Hence, considering the limiting factor lean six sigma and fuzzy logic methodologies were analyzing it further trying eliminating the constraint, finding out the root cause and optimizing the process. As a contribution of the research an analysis approach has been offered on individual operations of the manufacturing process in order to identify the bottleneck ones and on stepwise approach eliminate the constraints thus minimize the time for the overall production cycle.

4. The mathematical model and the criteria of minimizing the lead time of printed circuit board assembly process were analyzed on the basis of production management methods, in compliance with the quality requirements according to the standard IPC-A-610C. On this basis it has been proposed an optimization algorithm, which allows making the optimal choice of technological innovation on the criteria of minimizing the lead time of individual operation from the manufacturing process.

Improving the automatic printed circuit board assembly process using lean six sigma methodologies with combination of fuzzy logic allow minimizing the duration of the production cycle, in compliance with the quality requirements according to the standard IPC-A-610C. Six sigma methodology was used in order to know the characteristics of the manufactured product, as well as to improve the quality of process outputs by identifying and removing the causes of defects (errors) and minimizing variability in manufacturing and business processes. Lean production methodology was used in order to eliminate the defects of the manufacturing and thus increase the level of non-defect production. Analysis based on lean six sigma concepts allow having a broader view on manufacturing processes of the company in order to develop practical recommendations with respect to the requirements on the quality of the manufactured products. Last methodology used was fuzzy logic in order to replicate human reasoning and thinking to have the precise and predicted control of the manufacturing process. A mathematical model combining all the above methods shows the effective implementation of innovative technologies into the manufacturing process and optimization of the process of printed circuit board manufacturing.

As a contribution of the research a new model for lead time minimization of printed circuit board manufacturing has been designed based on description of quality control tools to be used from six sigma and lean production methodologies with application of fuzzy theory in order to find the optimal setup of the technological line for printed circuit board assembly process. A stepwise optimization of printed circuit board assembly process, which allows minimizing the lead time of production cycle, was offered with respect to requirements for quality described in standard IPC-A-610.

5. Optimization of the parameters of the manufacturing process and finding the optimal setup of the equipment in order to minimize the overall lead time is one of the main methods of effective implementation of innovative technologies into the production system. In order to integrate the innovative technologies into the existing and functioning manufacturing process, important fact to consider is to design a detailed quality management system scheme for interactions between processes. Optimization of the main processes of manufacturing process leads to increase of competitiveness of output product, as well as its quality. It was offered to design a quality management scheme of process interactions which will allow to significantly increasing effectiveness of management of the organization as well as functioning of the whole quality management system.

As main new contribution into the scientific area there were developed several methodologies, among those are: new criteria of effectiveness for implementation of innovative technologies into printed circuit board manufacturing process, mathematical model considering individual factors analysing the effectiveness of implementing innovative technologies for a manufacturing process, optimization of the process by minimizing the lead time of individual operation and thus minimizing the overall lead time for the overall manufacturing process, stepwise approach describing the usage of several modern quality control methods in order to minimize the lead time of production cycle. Such methodologies and approaches were analyzed on the example of printed circuit board manufacturing process, however the basis and logics of analysis can be applied throughout any manufacturing process in order to keep the output product highly competitive on the market, maintain the high quality of it and optimize the processes running in the production system to achieve flawless, non-defective, fast and reliable production. The results allow concluding as well that competitiveness of products increase within the optimization of the main processes of automatic assembly of printed circuit boards.

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PUBLICATIONS

Publications Related to the Thesis

For publications with multiple authors the share of joint authorship is equivalent.

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[A] Tarba, L., Mach, P. *Control tools for Process improvement in Electrical engineering.* 34th International Spring Seminar on Electronics Technology (ISSE), 2011. p. 220 - 224 ISSN 2161-2528

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- SGS14/187/OHK3/3T/13 Seven new quality tools from the perspective of current knowledge engineering